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FOREWORD

It is with great pleasure that we present the proceedings of the 17th Symposium on Lift and Escalator Technologies, 16-17 September 2026, organised by The Lift and Escalator Symposium Educational Trust.

The objective of The Lift and Escalator Symposium Educational Trust is to advance education in lifts, escalators and related technologies. The Trust is a Registered Charity No: 1170947 and is supported by The University of Northampton, The Chartered Institution of Building Services Engineers (CIBSE) and The Lift and Escalator Industry Association (LEIA).

Proceedings from the full conference series (since 2011) are available to download from www.liftsymposium.org. The proceedings are indexed in Scopus as "Symposium on Lift and Escalator Technologies", starting from the 2015 Symposium. Scopus is the world's largest abstract and citation database of peer-reviewed literature (scientific journals, books and conference proceedings), see https://blog.scopus.com/about.

The Society of Vertical Transportation (SoVT), a Society of CIBSE, is a specialist group for members who have an interest in vertical transportation. The SoVT meets regularly to promote technical standards, training and education, publications and various aspects of the vertical transportation industry. They direct the development of CIBSE Guide D: Transportation systems in buildings, the de facto reference on vertical transportation.

LEIA is the UK trade association and advisory body for the lift and escalator industry with a membership covering some 95% of the lift and escalator industry. LEIA members supply passenger and goods/service lifts, stairlifts, homelifts, lifting platforms, escalators, passenger conveyors and a range of component parts for such products.

LEIA members undertake the maintenance and modernisation of more than 250,000 products falling within the scope of the Association. LEIA provides advice on health, safety and standards matters, promotes education and training, especially through its distinctive distance learning programme.

The Symposium brings together experts from the field of vertical transportation, offering an opportunity for speakers to present peer-reviewed papers on the subject of their research. Speakers include industry experts, academics and postgraduate students.

The papers are listed alphabetically by first author surname. The requirement was to prepare an extended abstract, but full papers were accepted where the speakers preferred to offer them. The submissions are reproduced as they were submitted, with minor changes in formatting, and correction of obvious language errors where there was no risk of changing meaning.

 

Dr Richard Peters and Professor Stefan Kaczmarczyk
Co-Chairs and Proceedings Editors

CONTENTS

Establishing a Universal Relationship between the Traffic Mix in a Building and the Stops Data

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Keywords: The Round Trip, elevator, lift, incoming traffic, outgoing traffic, interfloor traffic, occupant floor, entrance floor, machine learning.

Abstract. Previous work has used machine learning techniques to model the relationship between stops data and their locations within a building with the type of traffic mix. The methodology required knowledge of the types of floors in the building (occupant floors or entrance/exit floors), and used stops data in the up and down direction on occupant floors and entrance/exit floors to infer the mix of traffic in the building. However, previous work was based on one specific building.

This paper extends the previous work in order to show that the relationship is independent of the number of entrance floors and occupant floors. Such a universal relationship would allow the use of this derived set of equations for any building regardless of the number of floors and passenger numbers.

For this purpose, the research in this paper will employ three different sizes of buildings in terms of number of occupant floors and entrance/exit floors, as well as the variation in the car capacity (i.e., number of passengers in each round trip).

The methodology will rely on the principle of normalisation. Moreover, a Monte Carlo Simulation tool will be used to generate the data required for training the machine learning model.

1 INTRODUCTION

This paper is a continuation of a series of pieces of research that attempt to infer the type of traffic in a building based on the number and type of stops that the lift makes. The following is a historical summary:

- As a simple example, the ratio of the up stops to the down stops can be used to detect the presence of an up-peak condition [1].
- A follow-up piece of work used artificial neural networks to assess the type of prevailing traffic in the building, such as up peak, down peak, two-way traffic or off peak [2].
- The concept of attempting to infer traffic data based on the number of stops was first suggested in 1992 [3] in what was then called the I-S-P method.
- Further work on this concept was carried out in 2022 [4], whereby the tables relating the expected number of stops in the up direction and the down direction were generated based on large amounts of data generated using the Monte Carlo Simulation (MCS) method.
- Basic single-dimensional regression was used in special limited traffic cases (e.g., where incoming traffic and outgoing traffic are equal) were then used in order to try to find simple ways that can be used to find the mix of traffic based on the number of stops [5].
- Machine learning was used in [6] to arrive at the equations that allow the user to infer the three components of the traffic mix in a building (i.e., incoming, outgoing and interfloor) from the normalised number of stops in the up direction and the down direction on occupant floors and entrance/exit floors. More specifically, there are four variables related to stops (later defined in section 4): average number of stops in a round trip in the up direction on the

entrance floors (USE); average number of stops in a round trip in the up direction on the occupant floors (USO); average number of stops in a round trip in the down direction on entrance floors (DSE); average number of stops in a round trip in the down direction on the occupant floors (DSO).

This paper relies heavily on the definition of a floor in a building as either an entrance/exit floor (to be referred to later as an entrance floor) or an occupant floor [7]. The previous paper to this work [5] systematically used two-dimensional regression to find specific equations that allow the user to find the incoming traffic and the outgoing traffic percentages from the four types of stops in a round trip.

This paper attempts to make such an equation more universal by varying the building size. Section 2 generates the required data into the so-called triangular table. Section 3 provides a visualisation of the resultant surface of the normalised number of stops against the mix of traffic. Section 4 carries out the two-dimensional regression on the data and consequently introduces the two resultant universal equations. Section 5 presents the final conclusions and suggestions for further work.

2 GENERATING THE TRIANGULAR STOPS DATA

Similar to the approach followed in the previous paper [11], data for the number of stops in a round trip on average was generated using the Monte Carlo simulation method (MCS), in a method similar to what was used in [7]. This resulted in the so-called triangular data tables. These were generated for the following cases:

- A building with 2 entrance floors and 8 occupant floors. The occupant floors were assumed to have equal populations. The entrance floors have an entrance bias of 30% for the lower entrance (e.g., B1) and 70% for the upper entrance (e.g., G). The car capacity was set to 13 passengers.
- A building with 3 entrance floors and 12 occupant floors. The occupant floors were assumed to have equal populations. The entrance floors have an entrance bias of 20% for the lower basement (e.g., B2), 30% for the upper basement (e.g., B1) and 50% for the ground floors (e.g., G). The car capacity was set to 20 passengers.
- A building with 4 entrance floors and 16 occupant floors. The occupant floors were assumed to have equal populations. The entrance floors have entrance biases as follows: 10% for B3 (i.e., lowest basement); 20% for B2; 30% for B1 (i.e., the highest basement floor); and 40% for the ground floor (e.g., G).

The mix of traffic was changed in each case by a value of 10% for each of the traffic mix elements. The traffic mix elements are incoming traffic (denoted by i/c, a number between 0 and 1); the outgoing traffic (denoted by o/g, a number between 0 and 1); and inter-floor traffic denoted by i/f, a number between 0 and 1). The sum of these three numbers should always be 1 (or 100%). The number of trials was set to 1 million for each case. This resulted in three triangular tables, each with 66 entries (11+10+9+8…..+2+1=66). These three triangular tables will be used to carry out the regression (as will be seen in section 4).

As was mentioned earlier, the raw data was generated using the Monte Carlo Simulation method. The MCS method can be used to faithfully generate large amounts of round-trip data [8, 9, 10, 11]. The MCS employs random sampling methods that ensure that the resultant data is a faithful representation of the parameters of the building. The MCS methodology does not need to generate the kinematics of the lift system or produce the speed-time profiles. Moreover, it does not need to carry out any allocation of landing calls to the cars. This makes the method independent of the dispatching algorithm. But more importantly, this is an excellent example of the abstraction capability of the MCS method, where it only generates the data that is needed for the case in question, rather than spending time generating kinematic curves or allocation calls. This approach speeds up the generation of the raw data.

3 VISUALISING THE TWELVE SURFACES

As was done in the previous paper, 12 surfaces will be visualised in this section in order to better understand the relationships, before attempting to find the final equations.

There are three independent variables: the percentage of incoming traffic, the percentage of outgoing traffic, and the percentage of inter-floor traffic. However, only two of these three are independent, as the sum of all three values must add up to 100% (or to 1.0). Thus, in reality there are only two independent variables (e.g., incoming traffic percentage and outgoing traffic percentage), as the third value will be dependent on the values of the other two. This is assuming that the inter-entrance traffic percentage is always zero.

In addition, there are four dependent variables. These are the average number of stops in a round trip. These four variables are:

- Stops in the up direction on entrance floors, to be denoted as USE.
- Stops in the down direction on the entrance floors, to be denoted as DSE.
- Stops in the up direction on occupant floors, to be denoted as USO.
- Stops in the down direction on occupant floors, to be denoted as DSO.

These four variables will appear later in this paper in the resultant two equations, but with the "hat" operator that reflects the fact that they are estimates derived from actual real-time measurements.

As there are two dependent variables, it is very convenient to plot each of the four variables as a "surface" against the two dependent variables. This results in four "surfaces" for each of the four dependent variables that have been plotted against the two independent variables. In this case, it has been assumed that the two independent variables are the incoming traffic percentage and the outgoing traffic percentage. So, in the plots that have been shown below, the x-axis and the y-axis are the incoming traffic and the outgoing traffic percentages, respectively.

Figures 1-4 all show a "triangular" surface that has been "curved". These figures belong to the original building (2 entrance floors, 8 occupant floors, and 13 passengers in the car per round trip) that was used in [6]. In two cases, the base of the triangle is at zero, either parallel to the x-axis or parallel to the y-axis, and the upper vertex of the triangle ends up on the other side. In the two other cases, the base of the triangle is at the top, either parallel to the x-axis or parallel to the y-axis, with the vertex near zero. The limiting number of stops is the car size and the number of occupied floors. Here, the number of stops saturate at about 6.3-6.6 stops per round trip, which is about 78.8%-82.5% of the number of occupied floors.

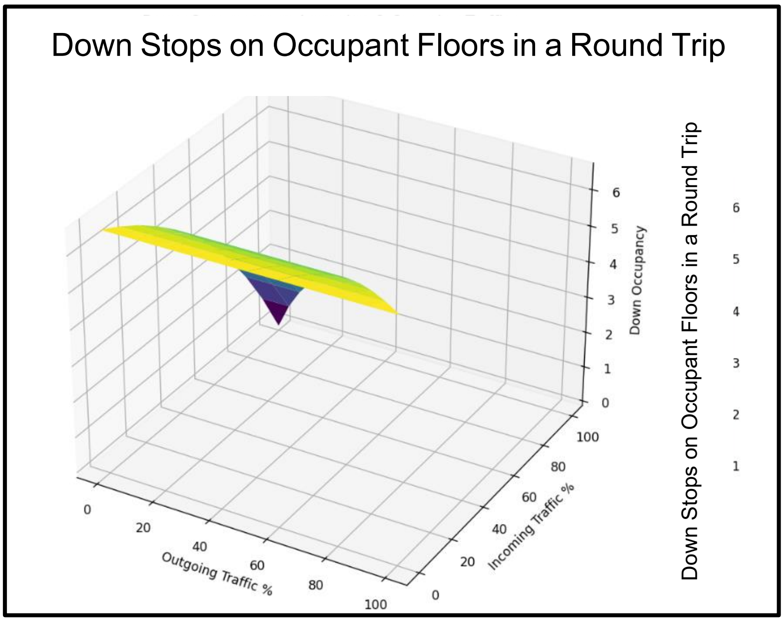


Figure 1 The plot of the surface that shows the number of down stops on the occupant floors during a round trip, plotted against the incoming traffic percentage and the outgoing traffic percentage

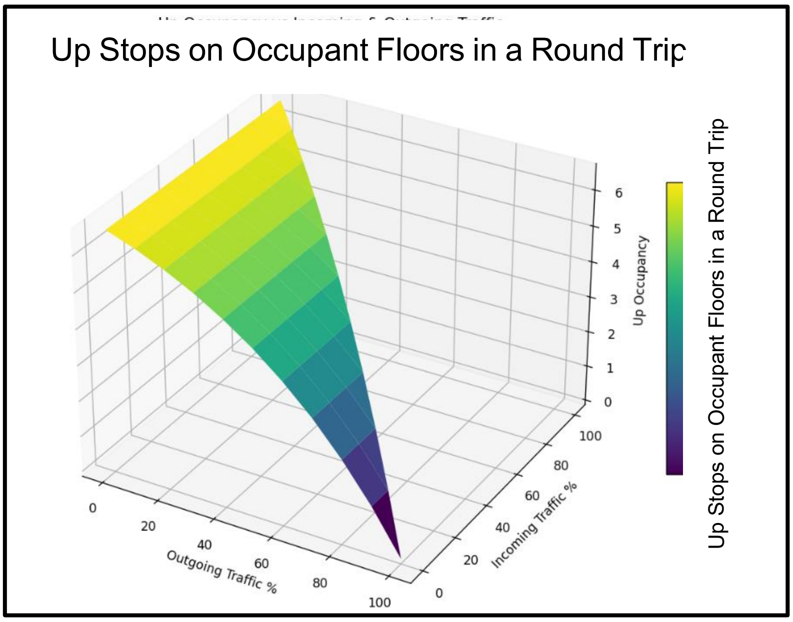


Figure 2 The plot of the surface that shows the number of up stops on the occupant floors during a round trip, plotted against the incoming traffic percentage and the outgoing traffic percentage

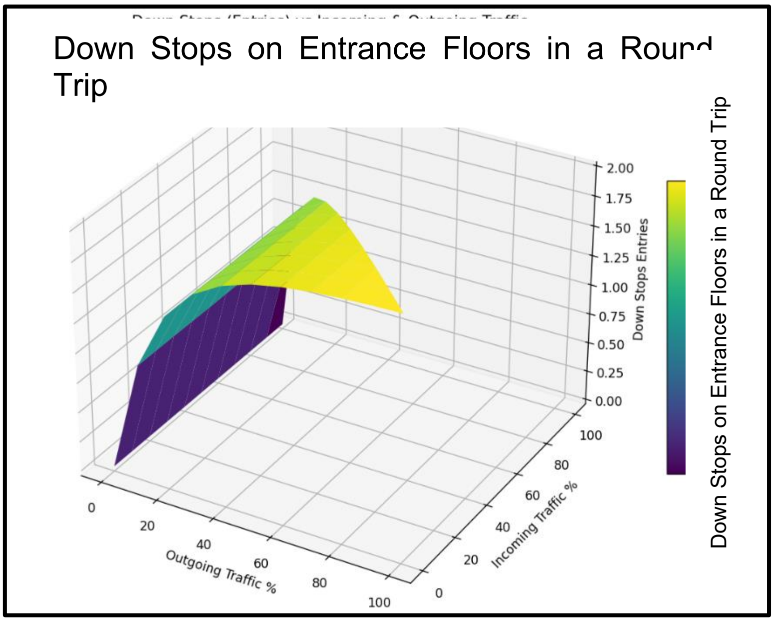


Figure 3 The plot of the surface that shows the number of down stops on the entrance floors during a round trip, plotted against the incoming traffic percentage and the outgoing traffic percentage

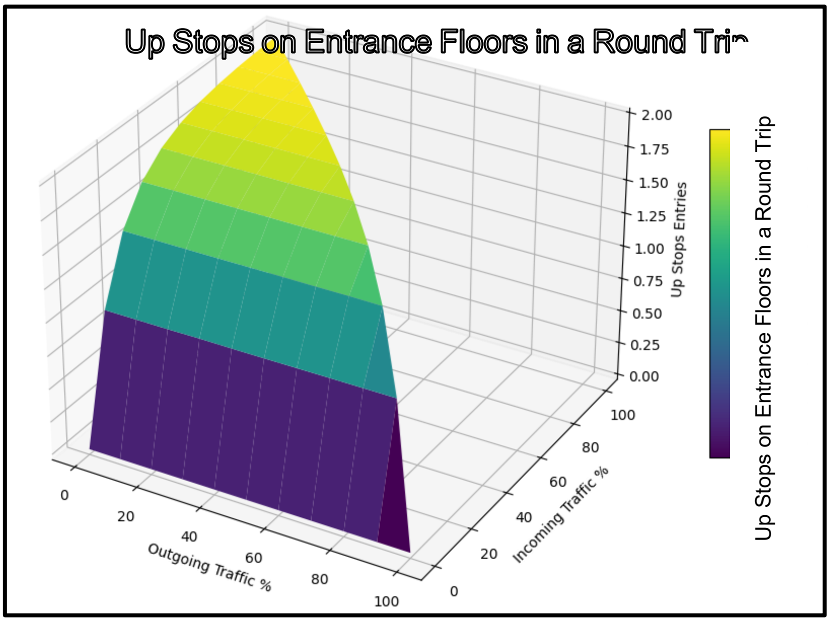


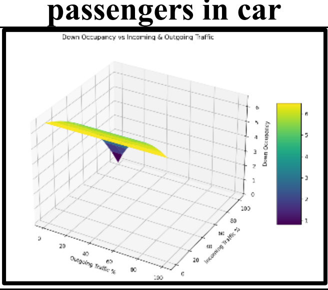
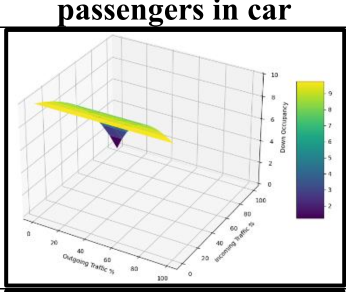
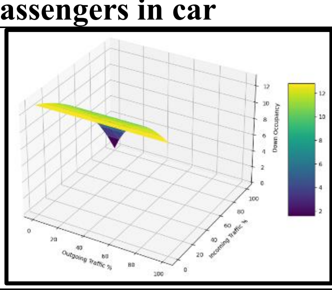
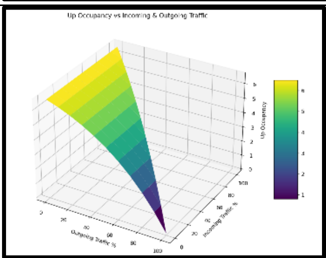
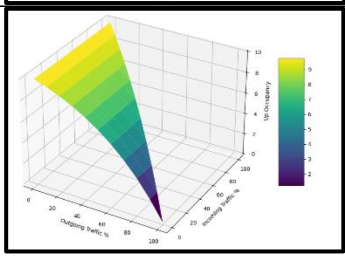
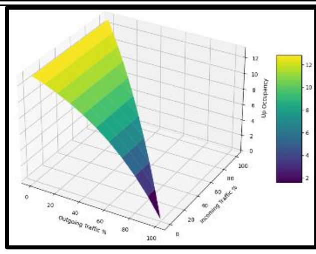
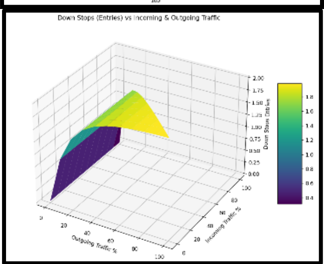
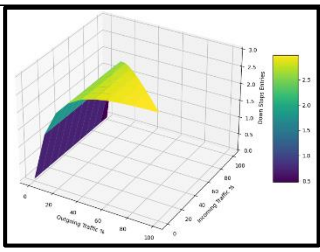
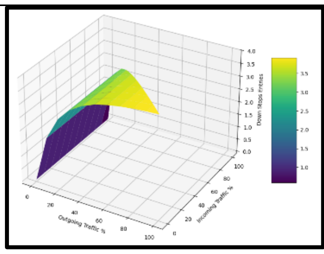
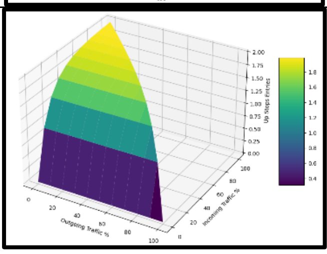
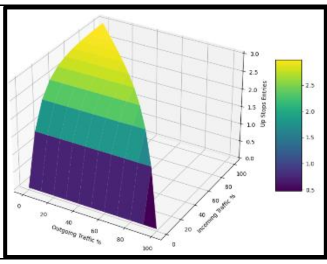
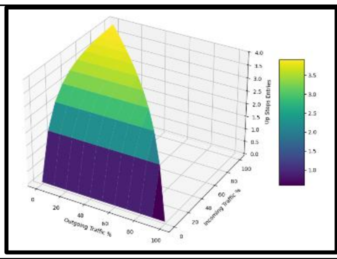
Figure 4 The plot of the surface that shows the number of up stops on the entrance floors during a round trip, plotted against the incoming traffic percentage and the outgoing traffic percentage

It is also worth noting that the z-axis in all four cases (i.e., the average number of stops in a round trip) has not been normalised and has been shown in absolute number of stops. Using further processing (as will be seen in the next section), the number of stops can be normalised by dividing by the maximum possible number of stops in the entrance floors (in this case 2) and by dividing by the maximum number of stops in the occupant floors (in this case 8). This will produce a "cube" that is normalised and in which each of the three sides is equal to 1 (or 100%).

These plots have been extended to another two sizes of buildings. In addition to the original building (2 entrance floors, 8 occupant floors, and 13 passengers in the car per round trip), two buildings were added: one with 3 entrance floors, 12 occupant floors and 20 passengers per car in a round trip; and a building with 4 entrance floors, 16 occupant floors and 26 passengers per car in a round trip. The set of 12 figures is shown in Table 1 below. It is worth noting that, for the purposes of normalisation, the number of passengers in the car was increased proportionately with the increase in the number of floors in the buildings (13 passengers for a total of 10 floors; 20 passengers for a total of 15 floors; and 26 passengers for a total of 20 floors: a ratio of around 1.3 passengers for every floor of the building).

By examining the 12 figures for the 3 buildings, it is obvious that the figures are nearly identical for the variables DSO, USO, DSE and USE. This shows that the characteristic of universality is valid. The behaviour of the normalised number of stops as a function of the mix of traffic in a building seems to be repetitive regardless of the size of building.

Table 1 Twelve figures showing the curved surfaces for the three buildings

	2 entrance floors/8 occupant floors/ 13 passengers in car	**3 entrance floors/12 occupant floors/ 20 passengers in car**	**4 entrance floors/16 occupant floors/ 26 passengers in car**
DSO			
USO			
DSE			
USE			

4 TWO-DIMENSIONAL REGRESSION RESULTS

As was done in the previous piece of work, MATLAB, two-dimensional regression tools were used in order to find the best fit equation that allows the user to find the percentage of the incoming traffic (i/c), the percentage of outgoing traffic (o/g), and the percentage of the inter-floor traffic (i/f) based on the four types of stops that take place on average during a round trip. The equations below were developed using two-dimensional regression tools. It is worth noting that these equations use the normalised values of the stops data, by dividing the average number of stops in a round trip by the maximum number of possible stops (i.e. the number of floors). The following is a list of the variables used in the equations below:

- i/c: incoming traffic (number between 0 and 1).
- o/g: outgoing traffic (number between 0 and 1).
- i/f: inter-floor traffic (number between 0 and 1).
- USE: The average number of up stops on the entrance floors in a round trip, normalised by dividing it by the number of entrance floors in the building.
- USO: The average number of up stops on the occupant floors in a round trip, normalised by dividing it by the number of occupant floors in the building.
- DSE: The average number of down stops on the entrance floors in a round trip, normalised by dividing it by the number of entrance floors in the building.
- DSO: The average number of down stops on the occupant floors in a round trip, normalised by dividing it by the number of occupant floors in the building.

Varying the number of floors (and fixing the ratio of passengers to floors) and carrying out the regression has resulted in the coefficients shown in Table 2 below.

Table 2 Coefficients that result from the regression analysis

	Number of Entrance floors	Number of Occupant floors	Number of passengers in the car	Constant	Up stops, Entrance floors (USE)	Down stops, entrance floors (DSE)	Up stops, occupant floors (USO)	Down Stops, Occupants floors (DSO)
Incoming Traffic Percentage	2	8	13	85.1098	22.0421	1.6454	3.4023	-109.0788
	3	12	20	85.7038	22.0810	1.7499	3.7070	-109.8847
	4	16	26	83.9512	23.6487	1.7416	3.2794	-109.1081
			Average	**84.9216**	**22.5906**	**1.7123**	**3.4629**	**-109.3572**
	Number of Entrance floors	Number of Occupant floors	Number of passengers in the car	Constant	Up stops, Entrance floors (USE)	Down stops, entrance floors (DSE)	Up stops, occupant floors (USO)	Down Stops, Occupants floors (DSO)
Outgoing Traffic Percentage	2	8	13	85.0430	1.8327	21.8450	-109.2628	3.7193
	3	12	20	85.6942	1.7356	22.0933	-109.8515	3.3576
	4	16	26	83.9551	1.7384	23.6424	-109.1039	3.2824
			Average	**84.8974**	**1.7689**	**22.5269**	**-109.4061**	**3.4531**

Doing the regression using the average values of the coefficients from the three buildings resulted in the two equations shown below. The variables USE, DSE, USO and DSO are the same variables defined on page 3 earlier in this paper, but the "hat" sign added here refers to the fact that the values in the equation are estimates. The first is the resultant regression equation to find the value of the incoming traffic:

$$\text{i/c}=\mathbf{84.9216} + \mathbf{22.5906} * \widehat{USE} + \mathbf{1.7123} * \widehat{DSE} + \mathbf{3.4629} * \widehat{USO} + (\mathbf{-109.3572}) * \widehat{DSO} \quad (1)$$

The second equation is the resultant regression equation to find the value of the outgoing traffic:

$$\text{o/g}=\mathbf{84.8974} + \mathbf{1.7689} * \widehat{USE} + \mathbf{22.5269} * \widehat{DSE} + (\mathbf{-109.4061}) * \widehat{USO} + \mathbf{3.4531} * \widehat{DSO} \quad (2)$$

The correlation coefficient from the two regression analysis results is very high and nearly close to one, showing an excellent correlation between the number of stops and the mix of traffic parameters:

i/c equation: R^2 Score: 0.990461

o/g equation: R^2 Score: 0.990467

Obviously, as the inter-entrance traffic has been assumed to be equal to 0, the inter-floor traffic can be found by subtracting the incoming traffic and the outgoing traffic from 1, as shown below:

i/f = 1 – i/c – o/g………..(3)

For example, if we know that incoming traffic is equal to 10% and the outgoing traffic is equal to 30%, then the interfloor traffic would be equal to 1-0.1-0.3 = 0.6= 60%.

It is worth noting that this methodology has assumed the inter-entrance traffic is always zero for simplicity. Future work will remove this constraint and allow the inter-entrance traffic to take on non-zero values. However, in such a case, the number of independent variables will rise to three (e.g., incoming traffic, outgoing traffic, and inter-floor traffic that does not add to one, as the inter-entrance traffic will not be equal to zero in this case). As such, it will not be possible to visualise the resultant "hyper-surface", because it will have four dimensions. Nevertheless, the fact that it cannot be visualised does not prevent finding the equation that links the mix of traffic to the value of the four types of stops. In such a case, three equations will be found for the incoming traffic, outgoing traffic and the inter-floor traffic. The inter-entrance traffic will be found by simply subtracting the three resultant values of traffic from 1.

5 CONCLUSIONS AND FURTHER WORK

This paper has attempted to build on previous work that explored the relationship between the normalised number of stops in the up direction and down direction on occupant floors and entrance/exit floors and the mix of traffic in a building (incoming traffic; outgoing traffic; interfloor traffic). This paper has further developed this work by attempting to show that such a relationship is universal.

The previous work developed the equations for one building only (namely 2 entrance floors; 8 occupant floors; and 13 passengers in the car per each round trip). This paper carried out the same analysis on two additional buildings: the first building had 3 entrance/exit floors, 12 occupant floors, and 20 passengers in the car for each round trip; the second building had 4 entrance/exit floors, 16 occupant floors, and 26 passengers in the car for each round trip.

Two dimensional regression was repeated for the relationship between the mix of traffic (namely for the incoming traffic percentage, a number between 0 and 1; and for the outgoing traffic mix, a number between 0 and 1) and the four types of stops (normalised stops in the up direction on occupant floors; normalised stops in the down direction on occupant floors; normalised stops up direction on entrance/exit floors; and normalised stops in the down direction on entrance/exit floors). All of these variables were normalised before applying the regression to them, in order to ensure that universality is found, assuming that it exists. Normalisation was carried out by dividing each of the stop variables by the corresponding number of floors in the building (e.g., the number of stops in the up direction on the occupant floors divided by the number of occupant floors in the building).

The results of the two-dimensional regression showed excellent similarity between the coefficients of the two equations (one equation to evaluate the value of the incoming traffic; one equation to evaluate the value of the outgoing traffic) with an extremely high value of the correction coefficient. The average of the four coefficients from the three sizes of buildings was suggested as the basis for the two universal equations.

There was no need to evaluate an equation for the interfloor traffic as it has been assumed that the inter-entrance traffic was always zero. Thus, the value of the interfloor traffic (a number between 0 and 1) could be simply found by subtracting the incoming and the outgoing traffic values from 1.

The next pieces of research will concentrate on the following:

- It is worth mentioning that as the building size was increased, the number of passengers in the car was increased by the same ratio. Thus, it is important to further understand the effect of the variation of the number of passengers in one round trip (i.e., the car size) on the coefficients of the two equations when such a ratio is varied.
- Applying the equations in practice on simulated data to assess the effectiveness of the method in finding the mix of traffic in a building based on real-time stops data.

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BIOGRAPHICAL DETAILS

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Ethics of AI in Lift Systems

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Keywords: artificial intelligence, ethics, lift systems, fairness, privacy, accountability, ownership

Abstract. Artificial intelligence is increasingly being integrated into lift systems, with applications in dispatching, traffic analysis, preventive maintenance and passenger-facing services. These technologies may improve efficiency, reliability, safety, accessibility and sustainability, but they also introduce ethical risks that have not yet been widely explored within lift research.

This paper argues that lift systems represent a distinct ethical context. They are shared, physical, safety-critical infrastructure embedded within buildings, and many users can't meaningfully opt out of using them. The ethical burden is therefore different from many consumer digital systems, where individual choice and consent are often treated as central safeguards.

As lift systems become more automated and data-driven, questions arise about prioritisation, surveillance, labour, environmental cost, commercial incentives, accountability and control. The paper proposes early guidelines intended to support industry discussion, future standards development and ethically aware technical research. The aim is to ensure that deployment of AI improves the systems people depend on while promoting fairness, equality, privacy, skills use, sustainability and accountability.

1 INTRODUCTION

1.1 Background

In 2025, the author published a technical paper which included a literature review of previously published research on the subject of AI in lift systems [1]. The paper classifies existing research by use case and speculates on future developments that could emerge as technology advances.

The paper includes a brief section on the ethical concerns accompanying these technological developments, concluding that "the industry has an ethical responsibility to care for its workers and passengers as well as the environment". It is noticeable how few papers cited in the literature review explored the ethical ramifications of the technological progress described in the research.

Unlike the previous research, this is not a technical paper. This is an ethics paper which explores the issues the lift industry will face as AI and automation continue to be introduced into systems that move people through buildings.

1.2 Scope

This paper focuses on AI, but some of the issues discussed also arise from automation more generally. A conventional rule-based controller can still raise ethical questions if it prioritises some passengers over others. A monitoring system can create privacy concerns even if it does not use machine learning. This wider scope is useful because AI is difficult to define precisely, and because many real systems combine statistical models, rules, sensors, cloud services and human procedures.

The paper does not provide a technical background on AI or the lift industry, as this was covered in the previous paper [1].

1.3 Ethical Framing

In many digital contexts, consent and choice are treated as central safeguards. Lift systems are shared, physical, safety-critical infrastructure embedded in buildings that many users can't meaningfully opt out of. A person with impaired mobility or a resident in a high-rise building may be unable to choose the stairs. This lack of meaningful exit changes the ethical burden. The focus must therefore shift from individual choice toward system-level responsibility.

2 ETHICAL RISKS

This section identifies seven ethical risk topics. The categories are not exhaustive, but they provide a practical structure for discussing how AI-enabled lift systems may cause harm if deployed without suitable safeguards.

2.1 Fairness

Lift service is shared, which means each dispatching decision can impact everyone in the system. A dispatching decision that improves one passenger's journey can worsen another's. For example, reducing the number of stops on someone's journey might shorten their transit time but increase another's waiting time. Prioritisation is therefore unavoidable in any dispatcher-based lift system. The ethical issue isn't whether lift systems prioritise, but which forms of prioritisation are justified and who decides. Priority for disabled users may improve fairness by compensating for a disadvantage. For example, a destination control system that monitors passengers and allows extra dwell time for a visually impaired passenger might improve accessibility without separating that passenger from other passengers, thereby making the lift system more inclusive. Paid priority, on the other hand, may reduce fairness by giving better service to those with greater economic power. A system that consistently provides premium tenants with better service may degrade the ordinary service available to everyone else and reduce the overall performance of the lift system.

In lift systems, a technically efficient outcome may still be unfair if it systematically disadvantages people who are already less able to use the building. Fairness can't be reduced to a single numerical target such as average waiting time but should instead consider context and the variance of passengers [2].

2.2 Privacy

AI-enabled lift systems may require data about passengers, lift movement and building use. Some data is low risk, such as aggregate counts of calls or stops. Other data can be highly sensitive, particularly where cameras, biometric systems or behavioural profiles are involved. Research on smart buildings shows that even apparently innocuous data, such as information about occupancy, can reveal private patterns when combined with other data [3].

A camera installed for passenger counting may also be capable of identifying employees, tracking visitors, analysing behaviour or supporting targeted advertising. AI ethics work on smart homes similarly identifies privacy, autonomy, transparency and fairness as key issues where AI systems observe domestic or semi-domestic life [4].

Advertising in lifts is not merely a question of visual annoyance. When combined with analytics, it can become a reason to identify, classify and monetise passengers in a space they can't meaningfully avoid. A phone user may be able to delete an application or change a setting, but a lift passenger can't change the data policy of the lift car.

2.3 Labour

AI-enabled preventive maintenance may reduce unnecessary inspections and help technicians arrive with the right parts, tools and information. This is a genuine benefit as it means lifts spend less time out of service, breakdowns may be prevented, repairs will be less error-prone, and technicians can focus on work that is needed rather than troubleshooting.

However, data-driven maintenance also changes the nature of work. If technicians are given a list of AI-generated tasks, their role may shift from diagnosis to execution. The skill required to interpret symptoms, understand unusual failures, and reason about the whole system may decline [5]. This risk is related to a well-known irony of automation: automated systems may remove routine human practice while still expecting humans to intervene successfully when something unusual happens [6].

Work changing because of AI isn't a problem in isolation; all technology changes work. The problems occur when workers aren't given the power, training and security to shape that change and when efficiency gains are captured elsewhere while workers bear the disruption. If expertise is allowed to decay, the industry may also become less resilient when automated diagnostics are wrong, incomplete or unavailable.

2.4 Sustainability

AI could improve sustainability in lift systems: better dispatching may reduce unnecessary travel, predictive maintenance may reduce avoidable component replacement and emergency journeys, and better expert design may reduce over-provision in buildings [1]. These are not trivial benefits, particularly in a sector linked to buildings and infrastructure [7].

At the same time, AI has environmental costs. AI depends on data centres, electricity, cooling, hardware manufacture and network infrastructure. The European Parliamentary Research Service identifies energy demand and environmental impact as gaps in many AI ethics frameworks [8]. The International Energy Agency reports that data centre electricity demand is projected to grow substantially as AI expands [9]. Recent work on water use also notes that AI and data centres can place pressure on water systems through cooling and electricity generation [10].

There is a risk that the lift industry will implement new systems that it sells as sustainable when it's actually just outsourcing the environmental impact to a different industry sector.

2.5 Incentives

Many ethical failures do not begin with malicious intent. They emerge when incentives reward behaviour that slowly degrades the system for users. Cory Doctorow uses the term 'enshittification' to describe the process by which digital platforms initially serve users well, then increasingly optimise for business customers and finally for the platform itself [11]. The word is deliberately abrasive, but useful because it captures a pattern of service degradation driven by commercial incentives, not bad actors.

A comparable risk could emerge in AI-enabled lift systems. A building may first use data collection and AI to improve passenger service; for example, a dispatcher may use facial recognition technology to anticipate a passenger's calls before they put them into the system. Later, the data from that system could be sold to a micro-managing employer tracking their employees' every movement or to an advertising agency that can target passengers against their will.

It's important to emphasise that this pattern should not be seen as a moral failing of the companies involved, but as a detrimental pathway that industries take when the economic system incentivises it.

2.6 Accountability

Accountability must be distinguished from blame. Blame asks who should be punished after a failure, while accountability asks who can explain the failure and how the system should change to prevent it from recurring.

Decisions about lift systems are distributed between many parties, including controller manufacturers, software suppliers, building owners, maintenance providers, consultants and operators. AI-enabled systems may spread this distribution further, making it harder to identify who is answerable when something goes wrong and increasing the risk that responsibility becomes obscured.

This risk is reinforced by organisational fragmentation. A lift system may involve multiple organisations, each with only partial control, making it possible for responsibility to be passed around the network. In some cases, harm may emerge not from a single negligent decision, but from the interaction of many reasonable local decisions. This can create accountability gaps which often lead to responsibility being misattributed.

One tendency is to shift responsibility onto the algorithm itself. If a dispatching system, maintenance model or passenger-monitoring system produces a harmful outcome, it may be said that “the AI decided”. This framing is misleading as an algorithm is not an independent moral actor. Treating it as the responsible party risks turning technical opacity into institutional evasion.

The opposite tendency is to blame the nearest human. Madeleine Clare Elish’s concept of the moral crumple zone is useful here. A moral crumple zone occurs when a human actor absorbs blame for the failure of a complex automated system, despite having limited control over it [12]. In lift systems, a technician, building manager or call-centre operator may be close enough to a failure to be blamed, but not powerful enough to have shaped the design, training data, commercial objectives or operating rules that produced it.

Whilst organisations who use fragmentation to obscure responsibility should be held accountable, ethical accountability should not require inventing fault where none exists. Some failures may be genuinely unforeseeable.

2.7 Ownership

The OECD Recommendation on Artificial Intelligence lists “transparency and explainability” as a core principle [13]. This paper argues that transparency is not sufficient and instead includes it as a prerequisite for ownership.

If passengers, workers and building users are affected by AI decisions but have no influence over the system’s goals, transparency alone can’t solve the ethical problem. Many of the risks identified in this section depend on who controls system goals, data and decision-making.

Ownership also concerns the means of computation. Lift companies are unlikely to start running self-hosted cloud platforms, meaning the lift industry will ultimately become dependent on a handful of cloud platform providers. Ethical decisions about access, prioritisation and surveillance may be made far from the people impacted by them. A future ethical framework for lift AI must therefore consider not only what systems disclose, but who has the power to shape them.

3 ETHICAL GUIDELINES

The following guidelines are offered as a starting point for industry discussion and future standards development. Their purpose is to respond to the risks identified above by suggesting practical directions.

3.1 Fairness

Prioritisation can't be eliminated from lift dispatching, nor should that be the goal of a fair dispatcher. However, the basis of prioritisation should be made clear during design and procurement rather than hidden inside an optimisation function, and the target should always be to use prioritisation to rebalance existing inequalities.

A useful starting point is to distinguish between prioritisation that compensates for disadvantage and prioritisation that reinforces advantage. Accessibility-related priority may be justified when it helps users access a building on more equal terms, whereas paid priority warrants stronger scrutiny because it may improve service for one group by degrading service for others.

Fairness could be expressed through constraints as well as optimisation targets. Minimum service levels, maximum disadvantage limits and accessibility constraints may be needed to prevent efficient systems from producing unfair patterns. In practice, this may mean that a dispatcher is allowed to optimise performance only within certain boundaries.

3.2 Privacy

AI-enabled lift systems should collect the least identifiable data necessary for the task. The ethical default should be to measure flows rather than identify people. Passenger counts, call data and car movements are often sufficient to improve dispatching or maintenance without collecting images, biometric data or individual behavioural histories.

There are two layers of limiting data collection. The first is to use low-resolution sensors such as light curtains, accelerometers and load sensors rather than cameras, biometrics and mobile-device tracking. This layer reduces the data points that can be misused. The second layer is to process the raw data close to the source and only store aggregated data in the cloud. Where cameras are necessary for counting passengers, systems should process video frames locally and upload passenger counts to the cloud, rather than storing identifiable footage in the cloud for processing there. In these cases where more intrusive sensing is proposed, the purpose should be narrow and justified.

3.3 Labour

AI should support expertise rather than quietly remove it. Predictive maintenance tools can improve lift reliability and help technicians work more effectively, but they should not reduce skilled workers to passive executors of instructions. A responsible system should explain why a task has been recommended, what evidence supports it and when the recommendation may be unreliable. Used well, AI could become a tool for continuing professional development, helping technicians understand patterns across many installations rather than simply telling them what to replace.

If technicians are expected to act on automated diagnostics, they should also be able to challenge, correct and improve those diagnostics. Their feedback should be treated as valuable training data, not as resistance to automation. This would make AI systems safer while preserving practical expertise and resilience when automated diagnostics are wrong, incomplete or unavailable.

However, participation and training do not fully answer the displacement problem. If AI-enabled maintenance reduces the labour required to maintain a portfolio of lifts, some workers may lose work. If AI-integrated robotics eventually becomes capable of performing more physical maintenance tasks, even more workers could be at risk of unemployment.

A responsible transition, therefore, requires serious industry discussion about retraining, redeployment, workload reduction and how efficiency gains should be shared. Otherwise, workers may be asked to help build systems that reduce their own bargaining power or employment security.

3.4 Sustainability

AI should be deployed where it improves total system sustainability, not merely local performance. A system that reduces lift energy consumption but requires disproportionate computation, hardware, cloud storage or sensor replacements may not be environmentally beneficial overall.

This requires comparison between possible implementations. AI should not be used simply because it is fashionable or technically possible. Designers should compare AI models, simpler automation, rule-based logic, calculation, simulation and conventional engineering improvements, considering both performance and environmental cost. Resource-intensive AI is more ethically defensible where it enables benefits that simpler methods can't provide, such as early fault detection from complex sensor data or adaptive accessibility functions. For example, if early fault detection reduces component replacement, emergency callouts and premature modernisation, it may be environmentally preferable even after accounting for the sensors, processing and data infrastructure required.

The aim should be to make the environmental cost of digital infrastructure visible in design decisions. If two approaches deliver similar benefits, the less resource-intensive approach should normally be preferred.

3.5 Incentives

If AI-enabled lift systems create new revenue streams through advertising, paid priority, or behavioural analytics, there will inevitably be pressure to optimise around those revenue streams at the expense of service quality. An ethical approach to incentives should therefore preserve competition, substitution and interoperability.

A building owner should not become dependent on a supplier because historic maintenance data, traffic data, diagnostic models or optimisation settings can't be exported or interpreted elsewhere. Open-source interfaces that allow interoperability and competition reduce the likelihood of enshittification. If a system is genuinely good, it should not need to rely on making exit impossible.

Some of these issues may ultimately require competition law or changes to existing rules that prevent interoperability, but the lift industry does not need to wait for a complete legal solution. Industry bodies and standards groups could require AI-enabled lift systems to meet basic anti-lock-in conditions. These might include documented interfaces, data portability, the ability to change analytics providers without losing essential records, and a clear separation between safety-critical functions and optional commercial services.

A successful ethical framework should not treat profit as the problem. The problem is a market structure in which profit can be increased by degrading service, restricting interoperability or trapping customers. The aim should be to create a system where companies make more money by maintaining high-quality, interoperable and long-lived systems than they would by lowering quality after customers are locked in.

3.6 Accountability

Accountability should make responsibility traceable without reducing every failure to blame. A fair accountability system must avoid both responsibility evasion and scapegoating. This does not mean that every failure must have a single guilty party, but it does mean that failures should not be dissolved into technical or organisational complexity.

The aim is to create systems that are auditable, explainable and learnable. When something goes wrong, the industry should be able to identify whether the problem was caused by poor design, poor configuration, inadequate maintenance, unforeseeable circumstances or some interaction between them. Accountability is not only about assigning responsibility after failure, but about ensuring that responsibility is visible before failure occurs.

3.7 Ownership

Ownership, in this context, should be understood as control over the system's purpose and direction, not merely possession of hardware or data. As AI becomes more embedded in lift systems, the industry's domain expertise should not be displaced by external cloud service providers whose priorities may be driven more by platform growth than by lift performance.

Democratisation does not mean every passenger configures the dispatcher, but that the values embedded in the system should be shaped by those with a legitimate stake in its operation. People such as building owners, maintainers, consultants, manufacturers, passengers and workers may not all need the same level of control, but they should not become passive subjects of decisions made entirely elsewhere. The choices that shape passenger experience and building operation should remain close to the lift system and the people affected by it.

A future ethical framework should ensure that the lift industry and its users retain meaningful power over what AI-enabled lift systems are for.

4 DISCUSSION

4.1 Possible futures

The same technologies could produce very different futures. In an optimistic future, AI-enabled lift systems improve accessibility, reduce unnecessary waiting, prevent breakdowns, support technicians and reduce waste. A visually impaired passenger might be guided to the right car without needing to identify themselves publicly. A technician might be sent to site with the correct diagnosis, tools and parts before a failure occurs. A building designer might use better traffic data to avoid both under-provision and unnecessary over-provision.

In a pessimistic future, the same technologies could enable surveillance, targeted advertising, paid priority, workforce deskilling and responsibility avoidance. A system originally justified by safety or service improvement might later be used for behavioural profiling. A dispatcher designed to improve flow might be tuned towards commercial priority. A maintenance system designed to support technicians might become a means of reducing skill, headcount and accountability.

The difference between these futures will not be determined by the technology. It will depend on governance, ownership, incentives and the industry's willingness to treat ethical design as part of engineering design.

4.2 Further research

This paper has attempted to organise the ethical problem space rather than solve it. Further research is needed to translate these early guidelines into practical tools for the lift industry.

The first area is measurement. The industry needs better ways to evaluate AI-enabled lift systems beyond average waiting time, local energy use or maintenance costs. Future work should investigate how fairness, privacy risk, environmental impact, resilience, accessibility and long-term service quality can be measured in ways that are practical for design, procurement and auditing. These measures will not remove the need for human judgement, but they may make ethical trade-offs easier to see and discuss.

A second area is governance. Further research should examine which issues are best addressed by changes to the law, technical standards, procurement requirements, industry body approval or professional guidance. Some problems, such as anti-competitive lock-in or misuse of personal data, may require legal intervention. Others may be better addressed through industry rules and standards of good practice. The lift industry should not wait for a perfect regulatory framework before beginning this work.

A third area is participation. If AI-enabled lift systems impact passengers, workers, building owners and maintainers, then the industry needs practical ways for those groups to influence how systems are designed and operated. This includes research into how expertise from technicians and consultants can be preserved, how passengers' interests can be represented, and how control over data and computation can remain close to the lift system rather than drifting entirely into external platforms.

Finally, ethics should not be confined to papers specifically about ethics. Often, those closest to a technical project are best placed to understand its ethical implications. Future lift research that develops the technological body of knowledge should therefore consider the ethical consequences of the work.

4.3 Declaration of AI use

In light of the transparency and accountability I have been espousing throughout this paper, it would feel wrong not to disclose my use of AI in conducting this research. Many of the sources cited in this paper were found by a large language model (LLM). I reviewed all the sources before uploading them to a new LLM instance, which was used to compose draft sections of the paper.

My previous paper on AI in lift systems was written in much the same manner.

The use of AI to assist with this research does not transfer any responsibility away from me. I take full responsibility for this paper, including the themes, narratives, conclusions and any remaining errors.

5 CONCLUSION

This paper identifies ethical risks raised by AI implementations in lift systems and considers how those risks may affect the people who use, build, maintain and govern them. It does not claim to provide finished solutions, but it sets out objectives that future solutions will need to meet if AI-enabled lift systems are to be fair, safe and accountable. It also argues that ethical reflection should become a normal part of technical research in the lift industry, rather than something considered only after systems have already been developed.

AI-enabled lift systems of the future should be fair, privacy-preserving and environmentally responsible. They should be supported by clear accountability structures, practical routes to challenge or exit systems, and governance arrangements that allow those affected by the technology to have meaningful influence over its development and operation. Workers in the lift industry, as well as the passengers who rely on lifts, should not be treated as passive subjects of automation.

As AI permeates the lift industry, a choice must be made. The technology can be allowed to develop without sufficient ethical scaffolding, risking surveillance, inequality, deskilling, responsibility avoidance and eventual enshittification. Alternatively, the industry can build that scaffolding early and deliberately. If it does, AI may help produce lift systems that are safer, more accessible, more sustainable and more accountable than those we have today.

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BIOGRAPHICAL DETAILS

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Development of an Ontology for Interoperability Between Lift Systems and Other Systems

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Keywords: lift systems interoperability, ontology, use case analysis.

Abstract. This paper proposes an approach to the development of an ontology for interoperability between lift systems and other systems. It introduces the concept of an ontology and gives examples of the services and roles of service users, in the context of lift operation, which might benefit from interoperability. An analysis methodology is discussed, which elaborates the use case "stories" for the service users, leading to the identification of requirements for information exchanges necessary to achieve interoperability. The collective information requirements may then be formalised into the technical definition of the interoperability ontology, and some specific examples are given.

1 INTRODUCTION

This paper proposes an approach to the development of an ontology for interoperability between lift systems and other systems. With increasing sophistication of building services and the systems which deliver them, in both commercial and residential property, the requirement for transparent interoperability between those systems is becoming urgent. Lifts, individually and as coordinated groups, offer a rich and diverse contribution to such an ecosystem of integrated building services. The systems and services, which might interoperate with lifts, are diverse (e.g. environment control, people flow, energy management, materials delivery and refuse collection, cleaning, access security, maintenance, etc.), and standardisation is seen as key to realising the necessary level of interoperability.

A service may have unique requirements of the information domain of lift operation, while at the same time, also having requirements which overlap with other services. It is the combination of all foreseeable service requirements that best identifies the scope and nature of the types of information required to enable interoperability. This paper describes an approach whereby the requirements for the types of information elements, and modes by which they are accessed, are identified by analysing each use case as a textual description or "story". Each story is elaborated from the perspective of a specific service user. Some overview examples are presented, which demonstrate that whilst a simple representation of the current state of the lifts is important, there is also a need for more complex information structures to support the requirements of the varied roles of each of the types of user of any service.

2 WHAT IS INTEROPERABILITY?

Characteristic of a rapidly evolving concept, there are currently various definitions of interoperability. Frequently mentioned aspects [1, 2, 3, 4] include:

- *Diverse systems* talk to each other
- *Share information*
- Applications *securely* and *automatically* exchange data

- *Cross-domain interoperability* - multiple social, organisational, political, and legal entities working together for a common interest or information exchange, irrespective of geographical, political or organisational boundaries.
- *Syntactic interoperability* - common data formats and communication protocols
- *Semantic interoperability* -
  - automatically *interpret* the information exchanged *meaningfully* and *accurately* in order to produce useful results as *defined by the end users of both systems*.
  - both sides must refer to a common information exchange *reference model*.

The European Union is actively promoting interoperability through the Interoperable Europe Act 2024 [5], the European Interoperability Framework (specifically semantic interoperability) [4, 6(sec5.3)] and data sharing through the European Data Governance Act 2024 [7].

For the current purpose, we are interested in identifying the requirements for semantic and cross-domain interoperability, i.e. lifts with other building services and users. This is the prerequisite for subsequent, though no less important, determination of the requirements for syntactic interoperability. In other words, we must know *what* the information is, before deciding *how* best to exchange it, taking into consideration any constraints of the operating environment. The result of the semantic analysis, the "reference model", is referred to as an 'ontology'.

3 WHAT IS AN ONTOLOGY?

Again, various definitions are offered, including: "An ontology is a *formal description of knowledge* as a set of *concepts within a domain* and the *relationships* that hold *between them*. It ensures a common understanding of information and makes explicit domain assumptions, thus allowing organisations to make better sense of their data." [8]

Other definitions [9, 10] that are relevant to semantic interoperability include:

- *Formal Definition*: A formal, explicit specification of a shared conceptualisation of a domain.
- Key Elements:
  - *Concepts (Classes)*: Categories of things (e.g., *lift*, *call*, *door*, *trip*).
  - *Properties (Attributes)*: Characteristics of concepts (e.g., a Lift *hasRegisteredCalls*, a Door *is locked*, etc).
  - *Relationships*: How concepts relate (e.g., a lift *travels to* a floor).
- Benefit – it acts as a:
  - shared *vocabulary*, ensuring that when one system says "direction," another system understands precisely what that means, facilitating data exchange, and
  - the *grammar,* ensuring that relationships are used meaningfully, allowing automated reasoning (e.g. a call is *assigned to* a lift, or a lift is currently *moving* in a direction, while it is *committed* to travelling in the opposite direction).
- *Formal Description* – the specification is:
  - coded in language understood by machines/computers (typically OWL)
  - published as text and diagrams understood by humans

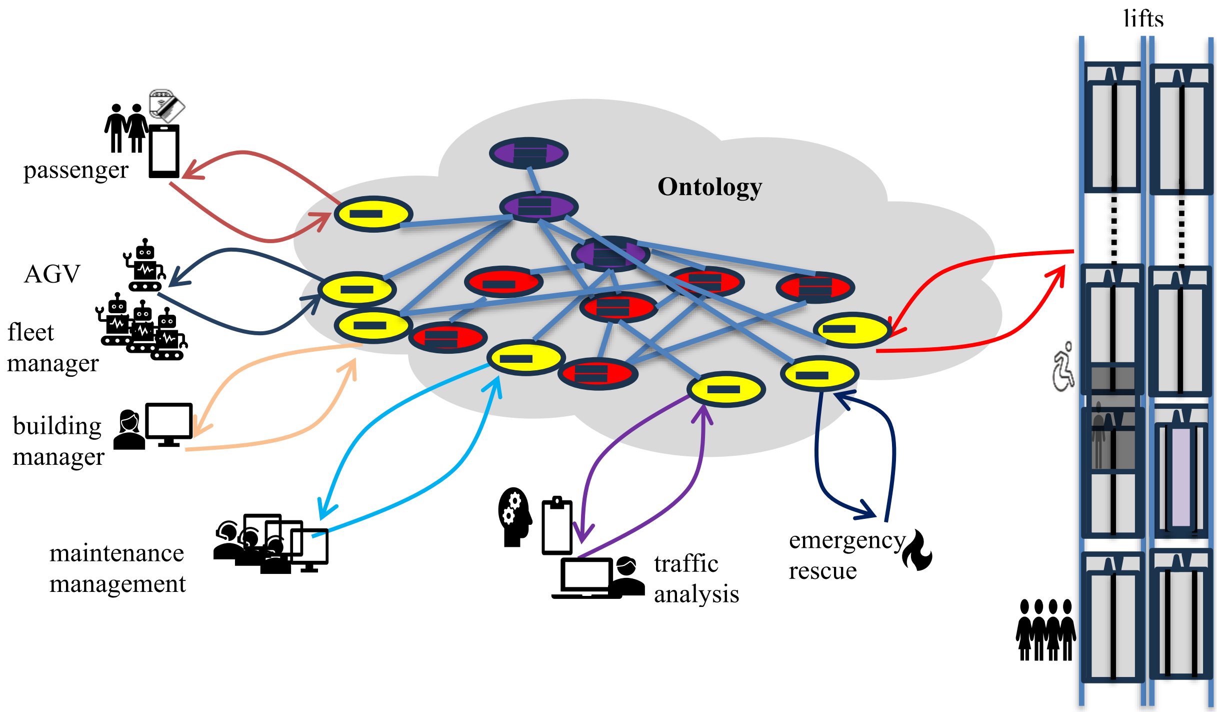

Figure 1 Ontology - supporting interoperability with lift systems

Figure 1 is a visual representation of how, in the lift domain, different types of user might interact (curved arrows) with elements of information (coloured ellipses), where the types of information and their relationships (straight lines) are defined by an ontology. The diagram is simplified for readability, and in reality, any user type will have multiple interactions with many types of information element. Note that no user interacts directly with the lifts or with any other user type.

Once the ontology is defined and published, it can be used to populate any number of information models with confidence that the information contained in each is consistent and interoperable.

4 INFORMATION MODEL

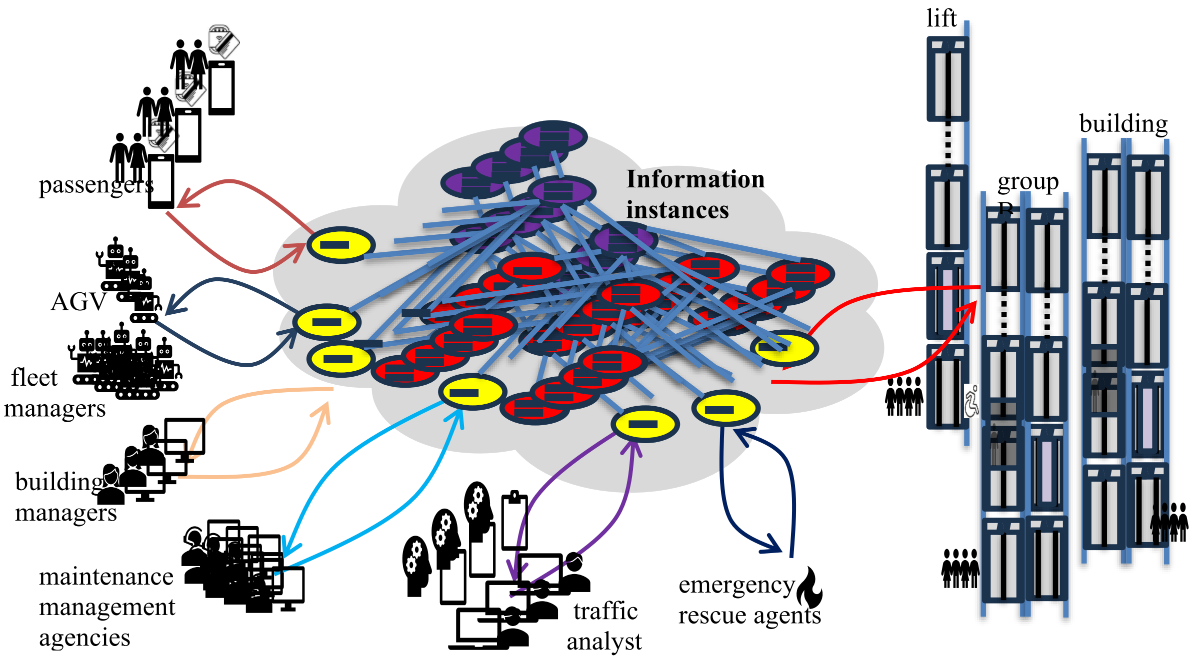

Figure 2 Information model – holds many individual instances of information as defined by an ontology

The ontology for lift interoperability describes the nature of the information of the domain – its concepts, structure and meaning – as a reference model. In the domain of lift operation, the types of entities and their interrelationships are expected to be stable, consistent and well-defined (i.e. standardised). In this case, an information model, which is distinct from the ontology that defines it, is the appropriate means both for holding instances of that information and for publishing it to support interoperability with other domains. The individual instances of the information itself – entities (e.g. the current state of each of the N lifts in Building X) – are held in an information model [11], using the datatypes and relationships that are defined by the ontology.

4.1 Information is accessed via nodes

To be able to address a specific individual instance within the information model, for example, to query the current state of a particular lift, or the state of one of its sub-components, key entity types are defined as nodes. Each instance of any node will have a unique identifier. The combined node address and identifier is referred to as a "resource identifier" [12]. A possible example might be[1]:

```
L4.NorthWing.CentralHospital@acommunity.health.uk/Door?DoorID=Rear
```

The resource identifier allows a precise logical identification of a specific element of instance information (i.e. the current state of the Rear doors of lift L4). However, using this

[1] NB While the resource identifier points to a unique resource, there may be more than one resource identifier pointing to the same unique resource. This simplifies the management of the resource (lift) by various agents/enterprises that may have different formats for cataloguing resources (e.g. following a change of service contract or a business take-over).

representation, the physical location where the information is held is neither explicit nor relevant. For this reason, the information model is represented in Figure 2 as existing within a cloud, isolated from its sources and users.

4.2 Information sources other than lift control equipment

The primary source of information for populating the information model of the lift interoperability ontology is obviously the lift(s). However, the analysis of requirements may identify dependencies on elements of information that, while they are specific to the domain of lift operation, are nonetheless not directly available from regular lift equipment and/or attached devices. For example:

- Static information: floor designations, travel times between floors, etc.
  This class of shortfall may be overcome with the introduction of:
    - manual input of data at the time of installation/configuration.
    - self-learning algorithms based on duration and direction of travel and stops made.
- Dynamic information: demand profiles, immediate contextual pre-history of a fault, door operation cycles whilst stationary, etc.
  This class of shortfall may be overcome with the introduction of:
    - additional software to provide "sensor fusion" [13], that combines and processes data collected from a number of physical sources and devices to provide more complex and richer elements of abstract information.
    - software to undertake logging and trend analysis.

The SAREF SmartLift [14(Sec 5.1)] technical specification, while not covering as broad a scope as discussed in this paper, includes assignment of a variety of different responsibilities amongst defined architectural elements, which comprise the Smart Lift System. These architectural elements can augment the lift control equipment to overcome such shortfalls.

4.3 Information model is distributed

The semantic interoperability ontology deliberately does not specify the location(s) where different elements of the information model are stored and maintained. Indeed, different types of information (or even different instances of the same type) may be held in physically distant locations. As indicated in Figure 2 – information conforming to the ontology reference model is best considered simply as a cloud. This allows great flexibility for a designer to choose devices and connections, from multiple suppliers, which are best suited to the available network, processing and storage infrastructure resources. Infrastructure technologies are rapidly evolving so that the restrictions that apply today may become irrelevant in one or two years, thus emphasising the importance for the ontology of its independence from infrastructure.

5 SUMMARY OF TERMINOLOGY

To summarise:

- The "semantic interoperability information exchange reference model" is defined in an ontology.
- Reference model (ontology) describes the nature of the information. It is standard and common to all lifts.

- An information model holds the current state (and logs) of the information for each individual lift and group of lifts.
- The ontology does not define the physical source of any type of information, nor where information is held. The information in the model should be considered in abstract terms, simply as a cloud.
- Independent decisions about network topology, data rates and storage capacities, etc., can be made to suit individual circumstances.

6 HOW TO DEVELOP AN ONTOLOGY FOR INTEROPERABILITY BETWEEN LIFT SYSTEMS AND OTHER SYSTEMS

The primary objective of interoperability is to make information available from a domain to users (humans and systems) in other domains that could benefit from it. This highlights the importance of the *user perspective* when gathering and analysing requirements for an ontology to support interoperability. In the following sections, a methodology is discussed for developing an ontology for lifts, which places the user perspective as the starting point.

Various methodologies are well documented, including [15, 16, 17] for capturing and analysing requirements of software systems, and specifically for the development of ontologies [18, 19], which can be summarised as:

1. Determine the domain and scope of the ontology –
   This is summarised in the Services and Roles lists in section 6.1.
2. Consider reusing existing ontologies –
   Section 6.2 discusses the contributions from existing work.
3. Enumerate important terms in the ontology to identify –
   Classes, relationships, properties, and rules governing permitted values. This is achieved by documenting requirements as use case “stories” (see section 6.3), followed by requirements analysis (see section 6.4).

6.1 Scope of services and user roles

Figure 1 shows generic examples of use, with implied roles and services. These must now be refined and catalogued. The following lists are typical of the services and user roles that might require interoperation with lifts. These are taken from the following references: CIBSE Guide D 2025 [20], SmartM2M [21]; Requirements & Feasibility study for Smart Lifts in IoT [22] and Singapore Standards standard for robot interface, TR93:2021 [23]. It is important to consider, as a separate use case, the interactions of each role with one or more services. This approach helps to ensure that specific requirements are not overlooked. However, although the listed services and roles represent a wide range of examples, it should remain easy to add further use cases, as required.

- *Services*: Status monitoring and management; Dynamic display of lift operation; External call registration; Pre-emptive/Predictive maintenance; Floor/Location-specific information delivery; Secure access control; Traffic analysis; Investigation of reported abnormal behaviour; etc.
- *Roles*: Standard passenger; Passenger with special privileges and/or accessibility requirements; Robot; Service technician (on-site/remote); Maintenance company;

Building manager; Building owner; Emergency service/Evacuation officer; Lift traffic design consultant; Accident investigator; etc.

6.2 Re-use of existing ontologies and schema

- *SAREF SmartLift* [21, 24] – considers requirements of different user roles and identifies different functional elements of an overall lift system. However, the scope of the information is not broad enough (for example, call registration and assignment are not covered), nor is there a deep enough level of detail of properties (for example, the logical operation of a lift travelling between floors).
- *Standard Elevator Information Schema* [25] – is a comprehensive and structured definition of the information types likely to be required, but as the name indicates, it is a schema and not an ontology. Therefore, it will be necessary to enhance certain aspects (e.g. the relationship between events and the functions of a lift to which they relate) to support the services and user roles.
- *Other standards* [26, 27, 28] – are useful references. However, while offering varying levels of syntactic interoperability, these do not provide the level of semantic interoperability necessary to support the target ontology.

6.3 Document information requirements by use case story

For each service and each type of user (role) of that service, a use case is developed, which includes a use case description or "story" [16]. This is a stepwise textual walk-through of the significant interactions (which can also be presented as a sequence diagram –Figure 3 Sequence diagram example – Call registration and service from external application Figure 3) between the user and the lift(s), with particular emphasis on the information required to be exchanged at each step. In this case, the detailed operation of the user interface (i.e. the presentation) is not significant, but rather the information content of the exchange must be clearly described (e.g. a lift is assigned).

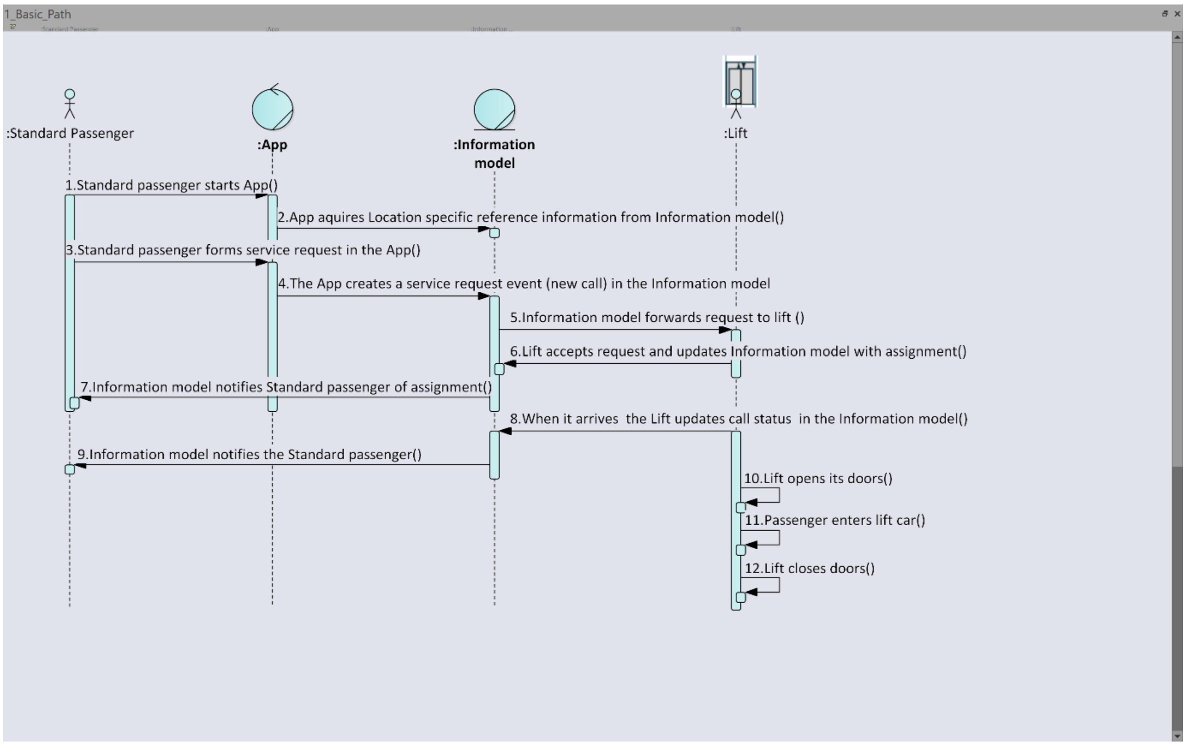

Figure 3 Sequence diagram example – Call registration and service from external application

The resulting use case story allows a thorough analysis of the information requirements, and each use case may contribute some new aspect that needs to be supported. It is a tool for deriving an ontology that is fit for purpose. At the same time, it helps to avoid duplication of, and contention with, other domains by supporting an analysis that highlights those aspects that are specific to the domain of lift operation.

6.4 Analyse information requirements

Once all the use case stories have been outlined, a more detailed and technically formal analysis may be conducted, this time to collect all the concepts of an ontology from the collection of use cases. The analysis results in an identification of the components of the ontology:

- *Resource* – how to find a specific information item (e.g. a specific lift in a group in a building/location)
- *Classes* – lift information is complex and often compounded of several properties which may themselves also comprise a number of properties, e.g. call, demand profile, fault event. As the analysis of requirements proceeds, a catalogue of these complex classes can be compiled. A careful definition of classes is essential for defining a robust and efficient ontology.
- *Property types* – simple data types which are nonetheless specific to the lift operation will also be identified, e.g. floor, direction, operating mode.
- *Relationships* – generally abstract, e.g. a lift serves a set of floors (or landings).

For the identified resources, the ontology will support the following access modes:

- *Query* – what is the current value of an information element (e.g. committed direction of a lift, load on the upper deck, etc)? Usually, a query language is supported, allowing the resulting information set to be filtered, focused, and possibly ordered according to query-specific criteria.

- *Event* – notification that the current value of an information element has just changed, e.g. doors now fully opened, fault event, etc. This will be time-stamped with the instant that the change occurred. Usually, an “observer” “subscribes” to a type of event to be notified each time that event occurs.
- *Request* – update the existing value (e.g. door open request) or create a new one (e.g. register a new landing call).

Additionally, the ontology will support:

- *Discovery* – publish the classes of resource information that are supported by this ontology. This can be used to identify the version and coverage offered by a specific instance of the ontology.

7 EXAMPLES OF SIGNIFICANT OUTCOMES OF ANALYSIS

In this section, some examples of more significant concepts are given, which identify dependencies on information that might not be obvious from the title of the use case alone.

- A passenger registering a call, having been identified and authorised by the access control system, should only be presented with the choice of destination floors which they are authorised to access. A similar list will be required of floors served by each of the lifts to which the call might subsequently be assigned. This indicates that a list of floors (defined as “*floorset*”) is a useful type of information element. The list is ordered by increasing relative height above the lowest floor, so that the building can be presented to passengers in a meaningful manner.
- Notification of exceptional behaviour to a service technician is more useful if the notification includes the *event context*. For example, if the exception occurs during travel, then the events that occurred during the trip leading up to the exceptional event provide valuable context. This indicates that in addition to the position and speed of the car at the time of the exception during travel, a *trip* (origin and destination floors, car load on departure) is a useful type of information element. This example highlights that in exceptional circumstances, which by their nature cannot be predicted, the detailed logging of events and status can be of significant value, whereas in normal operation this level of detail would simply represent a costly burden.
- The previous example of the benefits of associating an event with its context highlights the advantages, from the perspective of a user/system that is external to the lift information domain, of a combined view of the elements of information of a lift (current state and associated events), in terms of the *functionality offered*.
  Key functions (there may be others) are:
    - *Passenger access function* - Enable passenger access to the lift car (usually to operate the opening and closing of the doors). This is a cyclic function which starts and ends with a closed/locked state. Final context of an instance of the passenger access cycle includes timings of opening, closing and dwell operations, number of reversals, load on arrival, minimum load, and load on departure.

  - *Travel function* – Manage the safe standard movement of the lift from an origin floor to a destination floor. Again, this is a cyclic function, beginning and ending when the car is stationary at floor level.
  - *Service request function* – The acceptance of requests to travel (directional and destination landing calls, car calls, and parking calls). This function is not cyclic - it starts with a new call request and finishes when the call is no longer active (e.g. for a destination landing call, when the passenger is delivered to their requested destination floor).
- A *travel plan* for a lift – the sequence in which floors (landings) will be serviced by the lift – would be useful for an emergency responder during building evacuation.
- A *demand profile,* which is a statistical summary of demand over a period, per sample period as averages and other statistics, per floor and direction (or origin-destination pair if known), is needed when undertaking a traffic survey.

8 CONCLUSION

This paper gives an overview of the many aspects of analysing the requirements of an ontology which supports the interoperability of lift systems with other systems. Starting with a discussion of the objectives of interoperability and what is meant by an ontology, the paper presents these concepts in the specific context of the domain of lift operation.

A use case-based methodology for capturing requirements and their subsequent analysis is then discussed, and examples of important concepts are given, which are specific to the domain. This approach emphasises the user perspective, the essential quality for interoperability. It provides a stepwise analysis of the users' requirements for information. It also highlights elements of the required information model that may not be readily available from standard lift equipment, with the aim of prompting a discussion of how such requirements might be supported.

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BIOGRAPHICAL DETAILS

Jonathan Beebe has more than 40 years' experience in bringing software design and information modelling technologies into the domain of lift system control and monitoring. Throughout his career, Jonathan has maintained an active interest in research, resulting in the publication of the Standard Elevator Information Schema (SEIS) in 2003. Jonathan's research includes designs for a Global Dispatcher Interface (GDI), based entirely on the SEIS. He is currently developing an ontology to enable semantic interoperability between lift systems and smart buildings and cities, in which vertical transportation systems play a fundamental role.

AUTHOR'S NOTE

This paper is the result of independent thought and research spanning more than 25 years. At the time of writing, the author is actively contributing to the working group of the International Organization for Standardization (ISO), representing the British Standards Institution (BSI), on Approved Work Item: *ISO/AWI TS 8100-11, Lifts for the transport of persons and goods. Part 11: Interoperability between lift and other systems*.

The author confirms that this paper is original work and is neither published on behalf of nor endorsed by either ISO or BSI.

Escalator Step Entrapments

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Keywords: Escalator, moving walk, step-to-step entrapment, comb plate entrapment, step-to-skirt entrapment, prevention, friction, footwear

Abstract. The author of this paper has been engaged in a major research project to reduce the number of entrapments on escalators. Whilst the research covered all types of entrapments, this paper will focus on the types of entrapments that cause life-changing injuries, particularly to young children, including step-to-step entrapment, step-to-skirt entrapment and comb plate entrapments. Injuries include severe crushing and, in some cases, amputation. Examples of real-life accidents will be cited with a focus on methods of prevention. The research has revealed that these types of accidents can be reduced significantly, which has been confirmed by laboratory testing by a major escalator manufacturer.

1 INTRODUCTION

Entrapments on escalators are not a modern phenomenon. Cases can be traced back to the very early days of escalators. The original patent for an escalator was filed in 1859 by Nathan Ames in the USA, but the escalator that we are most familiar with today (2026) is a combination of the designs of Seeburger and Reno that were merged around 1935 when the two organisations were purchased by OTIS. A modern escalator has more safety features than those dating back to then, such as drop step switches, missing step detection, auxiliary brakes and so on, but apart from deflector brushes to keep feet away from the gap between the side of the step and the skirt, little has changed. In fact, the change in step design from wood to cast metal and the change in passenger footwear design from leather to synthetic materials has increased the risk of entrapment due to increased friction.

Three types of entrapment will be looked at in this paper:

1. Side-of-step entrapments
2. Step-to-step entrapments
3. Comb plate entrapments

Some entrapment cases, such as side-of-step entrapment or step-to-step entrapment, may lead to a comb plate entrapment.

Examples of entrapments can be seen below.

Figure 1 Side-of-step entrapment

Figure 2 Step-to-step entrapment that led to a comb plate entrapment

2 HISTORY OF ENTRAPMENTS

A literature search has revealed that the subject matter has been known for at least 56 years, yet entrapments are still occurring.

- 1970: UK Government ran a public information campaign on escalator entrapments on TV [1].
- 1973: Dr Campbell Reid publishes a paper entitled "Escalator injuries of the hand" [2].
- 1982: Carl White published a paper "measuring step clearances and inspection of escalators and moving walks" [3].
- 1984: HSE published PM34 entitled "Safety in the use of escalators" [4].
- 1984: HSE published PM45 entitled "Escalators: Periodic thorough examination" [5].
- 1996: D A Cooper presented a paper at Elevcon in Barcelona entitled "Escalator side of step entrapments" which was published in the trade press [6].
- 1996: B Fowkes presented a further paper at Elevcon in Barcelona entitled "Escalator side of step entrapments" [6].

- 1999: Directorate for Engineering Science in Maryland, USA, met to discuss escalator step-skirt entrapments [7].
- 1999: ASME met to discuss escalator safety, including friction and step clearances [8].
- 1999: Arthur D Little published a report entitled “Escalator step/skirt performance standard” commissioned by NEI [9].
- 1999: After the Arthur D Little report, ASME convened again to discuss the problem [10].

Then research went silent until:

- 2013: CPWR published a report, “Deaths and injuries involving elevators and escalators”, in which they call for the elimination of escalator entrapment hazards [11].

It is clear that the industry has failed to reduce entrapments to an acceptable level.

The phrase "we have known about it for a long time" implies long-standing awareness of a situation, often suggesting that actions or decisions should have been taken sooner. It highlights a gap between knowledge and action, frequently used to express frustration or the necessity of acting on existing information.

But entrapments are still happening at an alarming rate.

A report by TFL cited that there had been 55 foot entrapments on escalators in 12 months, of which 37 were children.

The number of entrapments reduced significantly during the global pandemic, but by 2024, it had nearly risen to pre-pandemic levels.

Escalator Entrapments 2018-2024

Introduction

Data

This report looks at incidents of escalator entrapment on the LU network between 01/01/2018 and 2025-04-11. Since the data extract for this report has been compiled using word searches, a small number of false negatives are likely, where entrapment incidents have been described with less typical spelling/vocabulary. The extract also contains three possible false positives. These incidents seem likely to describe escalator entrapment but it is not entirely clear, due to the short nature of the description and vagueness of language used.

50 incidents have been removed from analysis. 34 of these 50 have been removed because they pertain to dogs (usually their paws) becoming entrapped. The remaining 16 were removed because they pertain to the entrapment of fingers between the escalator handrail and UV sanitisers installed during Covid�they have therefore been excluded as time-specific and known-cause. Information on these excluded incidents can be found at the end of this report.

Foot Entrapments

Foot Entrapments by Year

293 foot entrapments across adults and children have been identified in the specified time period. Adult foot entrapments are comparatively rare, with only 74 of these 293 incidents representing adult entrapments, and 219 child foot entrapments.

So far in 2024, there have been 55 foot entrapments: 37 children and 18 adults.

The impact of the pandemic is clear in the reduced numbers in 2020 and 2021.

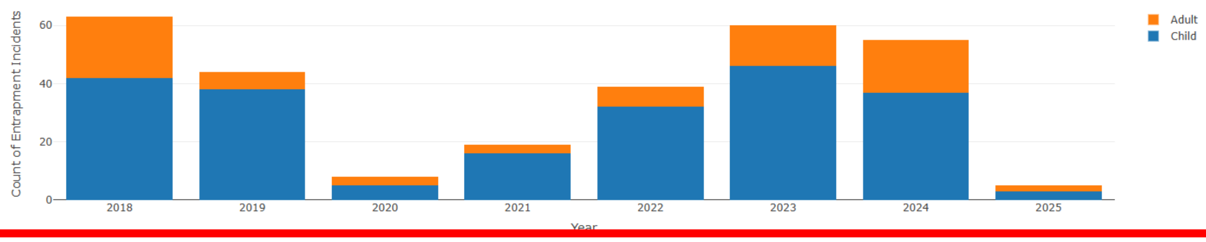

Figure 3 Report by TfL declaring 55 foot entrapments *so far* in 2024 [13]

3 ATTEMPTS TO REDUCE ENTRAPMENTS

Several designs and safety-related ideas have been tried, including:

1. Painting step demarcation lines
2. Raised step demarcation
3. Deflector brushes
4. Application of low friction surface coatings to skirts (not risers)
5. Painting footmarks on steps showing where to stand
6. Education of passengers

Painting step demarcation lines was an early idea which simply involved applying a yellow line around the outside of the step tread to indicate where not to stand. This is a similar approach to painting footprints on a step and is designed to indicate where not to place feet as opposed to where to place feet.

But entrapments still occur.

Raised profile step edges, similarly coloured, have been introduced and are designed to give a tactile indication to the footwear user that feet should not be placed in this area, but accidents still occur.

Figure 4 Side-of-step entrapment with raised step edge profile

Deflector brushes have been fitted as an option since the 1995 EN115 standard. Interestingly, the HSE in the UK issued a letter to the industry saying that, despite deflector brushes being optional in the standard, they expected them to be fitted to all escalators.

Nevertheless, entrapments still happen.

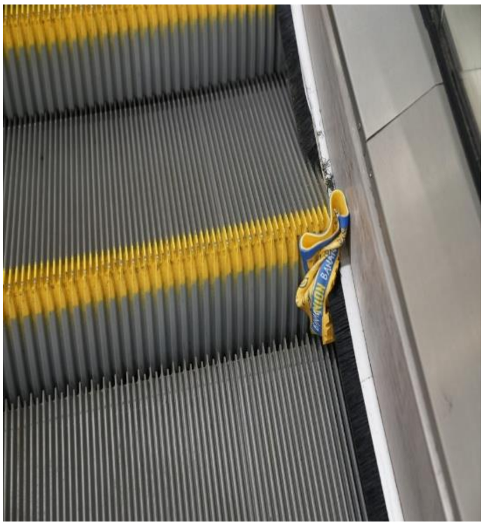

Figure 5 Side-of-step entrapment with deflector brushes fitted

There is research currently being undertaken into the effectiveness of different coloured deflector brushes. Some companies have moved away from the traditional black brush to a combination of red and yellow brushes, with red being used in the transition areas where the risk of entrapment is higher, and yellow on the incline. There is a theory under investigation at present that bright coloured deflector brushes actually attract children to place their feet into a risk zone.

In light of the data, there have been several more recent investigations and reports into escalator safety in general and/or entrapments specifically, including:

- 2024: London Underground published a paper "Guidance for enhanced escalator anti-entrapment features".
- 2024: TfL published its papers on escalator entrapments 2018-2024, from which the 55 entrapments previously mentioned were cited.
- 2024: Peters Research was commissioned by a major escalator owner to investigate accidents on escalators, including entrapments.
- 2025: LECS (UK) were commissioned by a major escalator owner and prepared a report entitled "Escalator entrapments avoidance".

4 FURTHER CONSIDERATIONS FOR REDUCTION IN ENTRAPMENTS

Apart from the application of a lubricant to reduce friction, which has been applied to skirt panels and continues to be required as part of some manufacturers' operating & maintenance manual, little has been done to reduce friction.

There is little the escalator industry can do to affect the shoe wear design market. All that can be done from an escalator industry perspective is to reduce the coefficient of friction at step risers and skirts and to educate passengers.

Reducing the friction at step risers has been researched and tested, and it has been found that the application of low-friction surfaces to step risers significantly reduces the risk of entrapment.

Figure 6 Escalators with low-coefficient step riser panels (which can be advertising or safety signs)

TKE published a report [12] in 2023 following testing of a low-friction application to step risers using a combination of advertising and safety messages on the step risers.

Its key findings were:

- Entrapment is influenced by multiple factors, including escalator geometry, operating conditions, and footwear characteristics.
- Softer footwear significantly increases the likelihood of entrapment, representing a critical variable in risk evaluation.
- Under the defined test conditions, steps equipped with advertisement panels demonstrated a reduced probability of entrapment compared to standard steps.

5 CONCLUSIONS

- Advertisement panels on escalator steps do not increase the risk of shoe entrapment.
- Under controlled test conditions, panels may contribute to a reduction in entrapment probability.
- The overall risk of entrapment for both configurations is considered very low under normal operating conditions.
- All tested configurations comply with applicable safety standards and code requirements.

It is recommended that the LEIA and EESF safety campaigns to educate children [13, 14] be introduced into mainstream curricula and that government public information films be reintroduced.

It is also recommended that reduced friction step riser panels be introduced as standard to all escalators (both new and existing).

The low coefficient of friction panels can be either safety notices, advertising panels or a combination of both. Where advertising panels are used, they can be used as a source of income for the escalator owner to self-fund the safety initiative.

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BIOGRAPHICAL DETAILS

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In 2012 David was awarded a CIBSE silver medal for services to the Institution, in 2021 he was awarded the Sir Moir Lockhead award for 30 years dedication to safety in the lift & escalator industry and in 2023 he was awarded an MBE for services to lift & escalator engineering.

He is a member of the Society of Vertical Transportation (SovT) Committee. He also serves on the CIBSE Board and is currently President. He is a past Honorary Visiting Professor at The University of Northampton and currently an Honorary Visiting Professor at The University of East London.

Beyond Aesthetics: How Cabin Finishes Influence Lift Design

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Keywords: Lift cabin finishes, Net usable area, Traffic performance, Accessibility compliance

Abstract. Modern lift cabin interiors have evolved into architecturally expressive spaces incorporating premium materials and integrated systems. While these finishes enhance perceived quality, they introduce significant engineering implications that are often overlooked during design. As lift-rated capacity and traffic analyses are typically based on bare cabin dimensions, the addition of interior finishes reduces the net usable area available to passengers, affecting passenger capacity, traffic performance and accessibility compliance.

This raises the critical questions:

Are traffic analyses based on accurate, real-world cabin conditions?

Do nominal car sizes continue to comply with accessibility standards once interior finishes are applied?

The paper identifies practical thresholds for assessing the impact of cabin finishes on lift design, highlighting the need to consider accessibility implications where finishes exceed 15 mm per wall and traffic performance implications where they exceed 25 mm per wall.

1 INTRODUCTION

Contemporary buildings increasingly prioritise interior aesthetics, with lift cabins evolving from purely functional enclosures into high-value architectural spaces. Finishes such as natural stone and composite panels are commonly incorporated to enhance user experience and align with design intent.

However, cabin finishes are often treated as architectural features rather than engineering design parameters. As lift-rated capacity, traffic performance, and accessibility assessments are typically based on bare-car dimensions, the resulting reduction in usable internal space may be overlooked. This can lead to overestimation of passenger capacity, reduced accessibility, and a gap between design assumptions and actual lift performance.

This paper evaluates the influence of cabin finishes on traffic performance and compliance with accessibility requirements. It argues that failing to consider finished internal car dimensions at the design stage can result in a consistent overestimation of lift performance.

To address this issue, the paper advocates early multidisciplinary coordination to ensure that interior design intent aligns with engineering performance requirements.

2 CONTEMPORARY TRENDS IN CABIN FINISHES

Modern lift design demonstrates a shift toward customisation and high-end finishes, including:

- Natural stone, engineered stone, composite panels
- Recessed handrails
- Concealed lighting systems in car walls

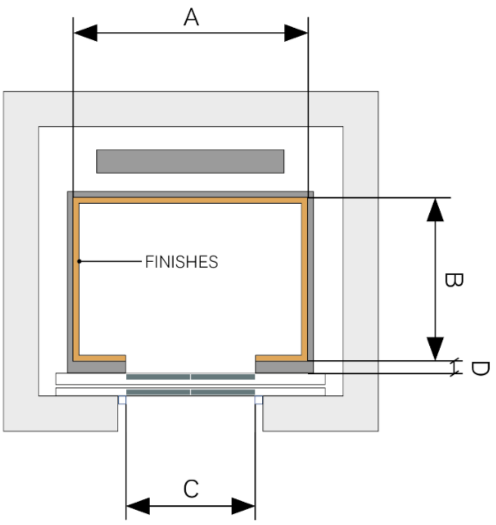
These solutions often require additional backing panels and support frames. As a result, wall build-ups can increase from 25–100 mm or more for premium installations. While visually appealing, the additional thickness reduces the lift's usable internal dimensions, affecting passenger capacity, traffic performance, and compliance with accessibility requirements.

Figure 1 shows the interior of the office lifts at ICD Brookfield Place, Dubai, incorporating finish build-ups of approximately 80 mm on each side wall and 25 mm on the rear wall, together with a recessed handrail.

Figure 1 ICD Brookfield Place, Dubai

3 LIFT RATED LOAD DETERMINATION

BS EN 81-20 [1] defines the permissible relationship between the rated load of a lift and its car area, with the rated load determined based on the bare car dimensions, excluding any internal finishes.



Maximum available car area = A x B
If D>100mm,
Maximum available car area = (A x B) + (C x D)

A – Bare Cabin Width
B – Bare Cabin Depth
C – Clear Door Width
D – Front Return Panel Thickness

Figure 2 Car area calculation for rated load – BS EN 81-20 [1]

ASME A17.1-2022 / CSA B44 adopts a similar approach by relating rated load to the net internal platform area, with an allowance of up to a 5% increase to accommodate design variations. However, modern cabin finishes often exceed this allowance, reducing the effective usable area.

Although this paper references the EN 81 series of standards, the issue is globally applicable. Lift performance is generally assessed using nominal dimensions, whereas actual performance is governed by finished internal conditions.

A lift may be capacity-compliant but still fail in accessibility or operational performance due to reductions caused by cabin finishes - "*Compliance ≠ usability.*"

4 FINISHES INFLUENCE ON TRAFFIC PERFORMANCE

Research by Dr Gina Barney [2] demonstrated that lift cars rarely achieve the theoretical passenger capacity implied by their rated load, as passenger accommodation is constrained by available floor area and personal space requirements rather than by mass alone. In practice, passenger capacity is therefore limited using an assumed area per person, typically 0.21 m². Dr Richard Peters' research paper [3] recommends addressing variability in passenger characteristics by adjusting the assumed area per person (e.g. 0.21 m² for offices and 0.3 m² for residential use, as recommended in CIBSE Guide D) [4], rather than by modifying loading thresholds.

The introduction of cabin finishes exacerbates this issue by reducing net usable internal area, thereby lowering effective passenger capacity, and increasing the divergence between predicted and actual performance. Consequently, reliance on nominal car area results in systematic overestimation of lift system capability.

Table 1 and Figure 3 illustrate the impact of cabin finishes on net usable car area and passenger capacity for a 1600 kg lift with car dimensions of 2100 mm (W) × 1600 mm (D), in accordance with ISO 8100-30:2019 [5]. The capacity reductions presented are specific to the car dimensions considered and will differ for other lift sizes.

Table 1 Impact of finishes thickness on passenger capacity

Scenario	Finishes thickness per car wall	Net usable car width	Net usable car depth	Net usable car area[1]	Maximum number of passengers per car[2]	Reduction in Capacity[3]
	[mm]	[mm]	[mm]	[m²]	Persons	
1	Nil	2100	1600	3.36	16	0%
2	15	2070	1570	3.25	15	6%
3	25	2050	1550	3.18	15	6%
4	50	2000	1500	3.00	14	13%
5	80	1940	1440	2.79	13	19%
6	100	1900	1400	2.66	12	25%

[1]Assuming same finish thickness on all four sides of the car wall.

[2]Maximum passenger capacity based on a passenger area of 0.21 m² per person

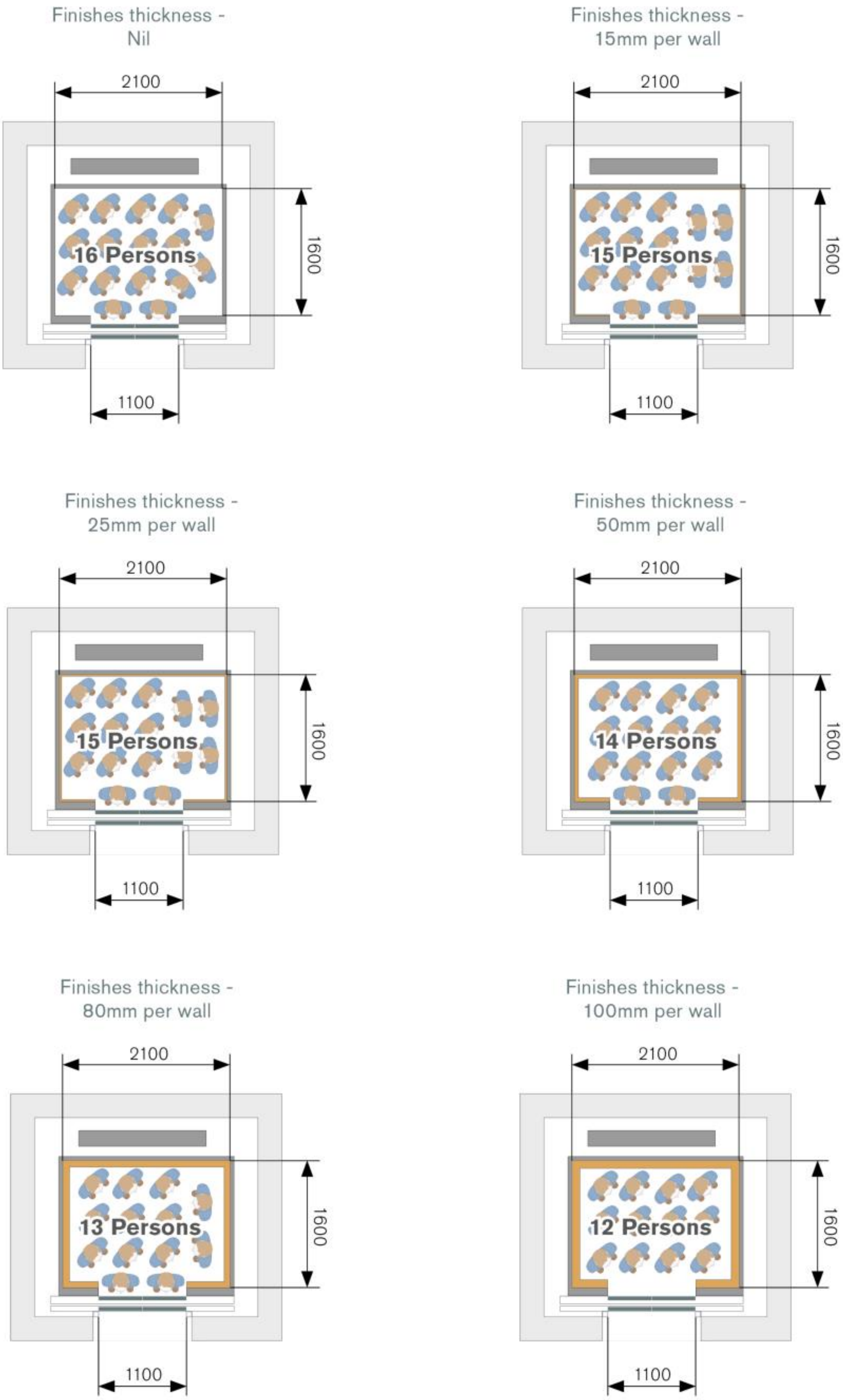


Figure 3 Maximum passenger capacity for a 1600kg lift with varying finish thickness.

The case study presented in this paper examines the impact of lift car finish thickness on traffic performance. The analysis considers a G+12 office building with a total population of 1,200 occupants, uniformly distributed at 100 per floor, with the ground floor serving as the main entrance level. The floor-to-floor height is 4.5 m.

Traffic performance was evaluated using a simplified simulation model under up-peak traffic conditions. The key modelling assumptions were as follows:

- Control system: Destination Control System (DCS)
- Passenger area allowance: 0.21 m²/person
- Capacity factor by mass: 100%
- Capacity factor by area: 100%
- Constant traffic demand over a one-hour simulation period

The lift system was assessed against the performance criteria specified in ISO 8100-32:2020 [6].

- Traffic condition: Up-peak (100% incoming traffic)
- Handling capacity in 5 minutes: 12%
- Average waiting time: 30 seconds

To evaluate the impact of cabin finishes on traffic performance, all building and lift parameters were kept constant, while the net usable car area was varied to reflect different finish thicknesses. Table 2 presents the traffic analysis results for each finish thickness scenario, including net usable car area, average capacity factor by area, average waiting time, and average time to destination. This enables a direct assessment of how reductions in usable car area, resulting from increased finish thickness, influence the overall performance of the lift system.

Table 2 Impact of finishes thickness on traffic performance

Lift Quantity	Lift Capacity	Lift Speed	Finishes thickness per car wall	Net Usable Car Area	Handling Capacity in 5 min	Average capacity factor by Area	Average Waiting Time	Average Time to Destination
	[kg]	[m/s]	[mm]	[m²]			[s]	[s]
5 Lifts	1600	2.5	Nil	3.36	12%	74%	29.1	80.4
5 Lifts	1600	2.5	15	3.25	12%	76.4%	29.6	81.0
5 Lifts	1600	2.5	25	3.18	12%	78.1%	29.6	81.0
5 Lifts	1600	2.5	50	3.00	12%	83.9%	31.7	83.8
5 Lifts	1600	2.5	80	2.79	12%	93.1%	129.9	188.1
5 Lifts	1600	2.5	100	2.66	12%	94.7%	651.8	738.5

The traffic analysis results show that the average waiting time remains within the design target of 30 seconds for finish thicknesses up to 25 mm. Beyond this point, performance begins to deteriorate. A significant non-linear increase in waiting time is observed at finish thicknesses of 80 mm and above, indicating that the lift system is approaching saturation.

Post-analysis assessment shows that average car loading exceeds the commonly accepted 80% occupancy threshold when the finish thickness exceeds 25 mm. Consistent with the observations of Dr Richard Peters [3], increasing waiting times indicate that the lift system is operating closer to saturation and is less resilient to variations in passenger demand.

The magnitude of this effect is not determined by finish thickness alone and will vary depending on factors such as lift capacity, building arrangement, control strategy, and traffic patterns. Nevertheless, the underlying principle remains the same: reducing the net usable car area reduces the effective carrying capacity of the lift system.

(Recommendation) Therefore, traffic analysis should always be based on the net usable internal car area to ensure a reliable and realistic assessment of lift system performance.

5 FINISHES INFLUENCE ON ACCESSIBILITY

BS EN 81-70 [7] is widely adopted as a global benchmark for lift accessibility, particularly in regions influenced by European engineering practices or lacking comprehensive local standards. The standard defines the minimum technical requirements for accessible passenger lifts.

It establishes baseline provisions to support independent access for a wide range of users, including those with mobility or sensory impairments, with the key principle that lifts shall be usable without assistance.

However, a compliance-versus-usability gap can arise in practice, as the application of cabin finishes may reduce usable internal space and limit the intended level of accessibility under real operating conditions.

Lift car design is therefore critical, as it directly determines:

- Wheelchair access
- Physical support and stability during travel
- Reachability of controls
- Effectiveness of sensory performance (visual, auditory)

For lift consultants and designers, the critical question is "*Can a diverse range of users enter, use, and exit the lift independently and confidently?*"

(Design risk) Failure to adequately coordinate architectural and lift design requirements can introduce significant risks, including accessibility non-compliance, reduced operational performance, and costly modifications or retrofitting following installation.

5.1 Wheelchair access

Finished internal dimensions play a critical role in ensuring that lifts are genuinely accessible in practice. The introduction of car finishes can significantly reduce usable space, thereby affecting accessibility by limiting wheelchair access and manoeuvrability.

BS EN 81-70 specifies the minimum lift car dimensions for different levels of accessibility. Type 2 lift cars (rated load of 630 kg) with internal dimensions of 1100 mm (W) × 1400 mm (D) represent the minimum accessible lift size for new buildings.

BS EN 81-70 further states that decorative finishes up to 15 mm thick on each wall may be disregarded when assessing accessibility compliance. However, thicker finishes reduce the usable car dimensions and may affect compliance with the minimum accessibility requirements.

Figure 4 illustrates the effect of 25 mm wall finishes on a Type 5 lift car (1275 kg rated load) with internal dimensions of 2000 mm (W) × 1400 mm (D). This lift type is commonly adopted as the minimum practical solution for accommodating Class A, B, and C electrically powered wheelchairs, as defined in EN 12184. The finishes reduce the clear internal dimensions, resulting in an effective car depth of less than 1400 mm. Consequently, the lift cannot be considered an accessible lift solution for a new building.

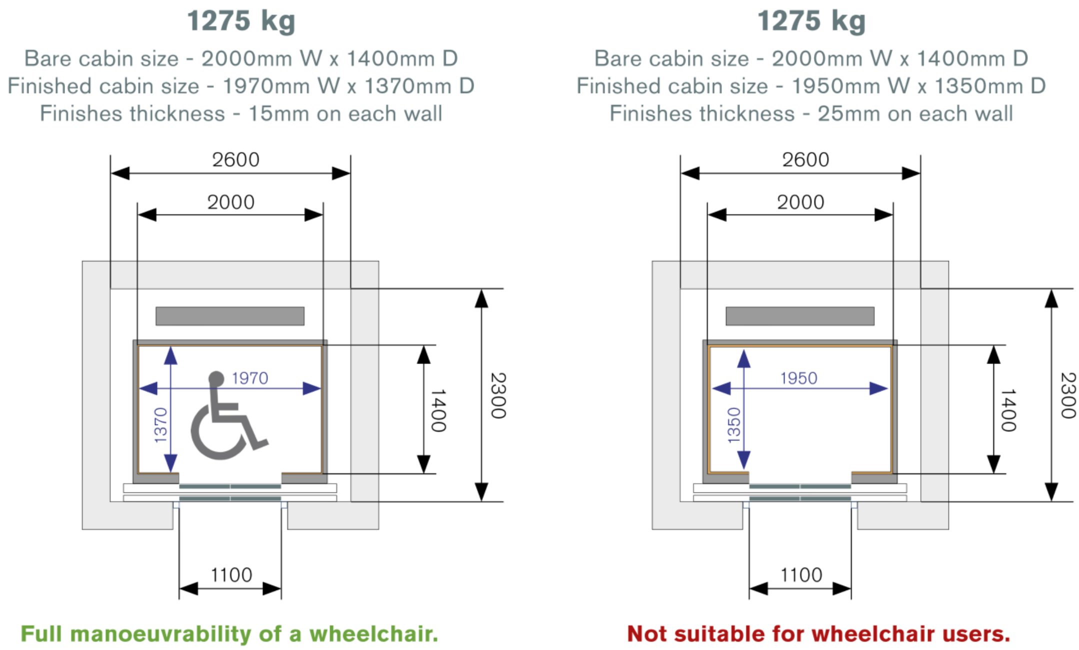


Figure 4 Finishes thickness impact on wheelchair compliance

(Recommendation) Accessibility assessments should be based on the finished internal cabin dimensions rather than the bare cabin dimensions. This ensures that the installed lift provides the required wheelchair accommodation and remains compliant with the accessibility requirements of BS EN 81-70.

5.2 Physical support and stability during travel

Handrails enhance safety and comfort not only for ambulant disabled users, but also for elderly passengers and others with reduced balance or mobility.

BS EN 81-70 requires a handrail to be provided on one side wall of the lift car, typically the wall containing the car operating panel. For lift car Types 4 and 5, a second handrail is required on either the opposite side wall or the rear wall (Code Requirement – BS EN 81-70). While providing handrails on all non-door walls is recommended as good practice, it is not a mandatory requirement of the standard.

Handrails are a key accessibility feature and must comply with specific dimensional criteria, including a graspable circular profile with a diameter of 30–45 mm and a minimum clearance of 35 mm between the handrail and the wall. These requirements are intended to ensure that passengers can maintain a secure and comfortable grip while travelling.

However, certain design solutions, such as recessed handrails or flat bar handrails (as shown in Figures 5 and 6), may not meet these requirements. These arrangements can restrict effective gripping space, reduce hand clearance, and make it difficult for users, particularly those with limited mobility, reduced dexterity, or visual impairments, to maintain a secure and continuous grip. This can compromise both safety and usability.

Figure 5 Recessed handrail

Figure 6 Flat bar handrail

5.3 Reachability of controls

BS EN 81-70 requires the car operating panel (COP) to be positioned on the side wall, enabling passengers, including wheelchair users, to access the controls directly after entering the lift car without the need for additional manoeuvring.

Figure 7 illustrates an alternative COP arrangement, where the panel is located on the front return wall to achieve a cleaner architectural appearance on the side walls. This arrangement is commonly seen in older installations and in countries where BS EN 81-70 is not the governing accessibility standard. However, it can present accessibility challenges, as wheelchair users may need to reposition themselves within the car to reach the controls after entering. Consequently, the side-wall COP arrangement specified by BS EN 81-70 provides superior accessibility and ease of use.

It is also important to ensure that lift controls remain within the reach limits specified by BS EN 81-70 for wheelchair users. The standard recommends that car operating panel buttons are positioned between 850 mm and 1200 mm above the finished floor level.

Figure 7 COP on front walls (Emaar Square, Dubai)

5.4 Sensory Performance

5.4.1 Visual Performance

Reflective or uniform materials (e.g. polished metals, mirror stainless steel) may cause glare and reduce luminance contrast, making controls and signage harder to identify.

To maintain visual performance:

- Sufficient luminance contrast between controls, signage, and background surfaces in accordance with BS EN 81-70 / ISO 21542 [8] should be provided.
- Highly reflective finishes near the COP and indicators should be avoided.
- Transparent elements should be designed to minimise visual discomfort; in high-rise applications, their use may be limited where excessive exposure affects user comfort.

(Recommendation) Visual conditions should be verified on site, as lighting and reflections can reduce performance after installation.

5.4.2 Auditory Performance

Cabin finishes can degrade auditory performance by causing:

- Uneven induction loop signal
- Increased reverberation and reduced speech clarity

As a result, systems meeting design criteria may underperform after the installation of finishes.

(Recommendation) To ensure effective auditory performance, the induction loop field strength should be maintained at 400 mA/m (RMS) ±3 dB (283-566 mA/m) across the lift cabin in accordance with IEC 60118-4 [9] and verified on site following the installation of cabin finishes.

6 OTHER IMPACTS

Shaft Constraints: Increasing the bare cabin size to compensate for the finishes may require a larger lift shaft, which can be difficult to accommodate at later stages of the design process.

Additional Car Mass and Equipment Selection: Lift manufacturers typically allow an additional 300-800 kg for cabin finishes, depending on the rated load. Where the weight of cabin finishes exceeds the manufacturer's standard allowance, additional assessment may be required to verify the suitability of the lift equipment, safety components, and certification status [10].

Higher Electrical Demand: Excessive finish weight may increase motor size requirements and electrical power demand.

Fire Safety: BS EN 81-20 [1] requires the supporting structure of the lift car body to be non-flammable. Furthermore, materials used for the car walls, floor, and ceiling should comply with EN 13501 or relevant local fire performance requirements. Decorative finishes, laminates, composites, and adhesives can contribute to fire load, smoke generation, toxicity, and flame spread, and should therefore be carefully evaluated during material selection.

7 CONCLUSION

The key thresholds identified in this paper are 15 mm and 25 mm of decorative finishes per wall. BS EN 81-70 permits finishes of up to 15 mm per wall to be disregarded when assessing accessibility. Beyond 15 mm, the impact of finishes should be explicitly considered in accessibility assessments. Where the build-up exceeds 25 mm, the effects on traffic performance should also be assessed. These thresholds demonstrate that cabin finishes can no longer be regarded as purely architectural elements and must be considered as part of the lift design process.

A coordinated design approach is therefore essential, supported by the following key actions:

- Early definition – Define cabin finishes during the concept / schematic design stage.
- Space planning – Allow for finish thicknesses in initial space planning.
- Traffic analysis – Include finishes in the internal car area in traffic calculations.
- Accessibility compliance – Verify that the finished car dimensions remain suitable for wheelchair users and that handrail designs and car operating panel arrangements comply with accessibility requirements.
- System checks – Review impacts on lift equipment selection, electrical demand, and fire safety requirements.

While nominal car dimensions may guide early planning, actual lift performance depends on the finished internal dimensions available to passengers. By considering cabin finishes from the outset and coordinating them throughout the design process, project teams can ensure that lifts achieve their intended accessibility compliance and operational performance.

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BIOGRAPHICAL DETAILS

Vignesh Dhanapal is currently working as a Senior Vertical Transportation Engineer at Foster + Partners, London.

He began his career as an installation engineer in India and has over 10 years of experience in the Gulf region as a Vertical Transportation Consultant.

He has expertise in the design, planning, and delivery of vertical transportation systems for complex high-rise and mixed-use developments, with a focus on performance optimisation, accessibility, and compliance with international standards.

From Cloud to Control Cabinet:
Edge AI for the Next Generation of Lift Monitoring

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Keywords: Predictive Maintenance, Edge AI, Condition Monitoring, Lift Monitoring, Neural Processing Unit, Hybrid Cloud-Edge Architecture, Anomaly Detection, Expert System, Sensor Fusion, Model Adaptation

Abstract. Predictive maintenance has become a key enabler for improving the reliability, availability, and lifecycle management of modern lift systems. Current solutions typically rely on connected sensor devices that transmit operational data to cloud-based platforms where advanced analytics and artificial intelligence (AI) models are executed. While this architecture enables powerful diagnostics and fleet-level insights, it introduces dependencies on connectivity, latency constraints, and additional data transfer requirements.

This paper presents the next development stage of a predictive maintenance system for lifts in which artificial intelligence models are executed directly on-site at the edge device installed within the lift system. The approach builds on an existing cloud-connected monitoring architecture in which substantial preprocessing and feature extraction already take place locally. However, until now, the final inference of the deep learning models has been performed in the cloud. By introducing an enhanced hardware platform equipped with dedicated Neural Processing Units (NPUs), it becomes possible to execute Deep Neural Network (DNN) models locally while maintaining acceptable processing time and energy consumption.

Running complex DNN models on embedded systems presents a significant challenge due to limited computing resources. Although NPUs can accelerate neural network inference compared to CPUs, this can lead to trade-offs between speed and model accuracy. Therefore, a balanced approach is necessary. Initial results from the presented architecture are promising and enable predictive real-time diagnostics directly within the lift system. This reduces reliance on cloud connections, improves response times, and paves the way for more autonomous and scalable predictive maintenance solutions in the lift industry.

1 INTRODUCTION

The requirements for modern lift monitoring have changed fundamentally in recent years. Building owners and operators no longer expect merely the reporting of faults that have already occurred; they increasingly require information about the future condition of their installations. The objective is to plan maintenance activities according to actual needs, prevent unplanned downtime, and optimise the economic utilisation of technical components.

Machine learning techniques, and particularly Deep Neural Networks (DNNs), offer significant potential in this context. To date, such methods have predominantly been deployed within cloud infrastructures, as both training and inference require substantial computational resources. However, the increasing availability of powerful embedded hardware now enables key elements of artificial intelligence to be executed directly on monitoring devices installed on-site.

The transition from cloud-based AI to Edge AI should not be regarded as a replacement of existing architectures, but rather as their logical evolution. The central question is therefore not whether cloud or edge computing is superior, but which tasks should be performed most effectively at which location.

2 FROM DATA COLLECTOR TO LOCAL DIAGNOSTIC NODE

Since 2004, the author's company has installed a five-figure number of lift monitoring systems worldwide. Initially, these systems represented an approach that had little connection to artificial intelligence. The foundation of the system is the continuous acquisition of operational data directly from the lift installation. Motion profiles, load and travel events, condition parameters, signal characteristics, and derived features are collected in such a way that meaningful technical conclusions regarding the condition of the system can be drawn.

This existing data infrastructure represents a significant strategic advantage. Many AI projects fail not because of a lack of algorithms, but due to insufficient historical data, inadequate data quality, or non-reproducible preprocessing methods. The monitoring platform already incorporates an architecture in which substantial preprocessing is performed locally. Raw data is filtered, condensed, and transformed into features suitable for diagnostics and trend analysis. While cloud-based evaluation enables the use of powerful models, it also requires reliable connectivity and introduces additional communication and operational requirements.

The transition towards Edge AI therefore represents a natural extension rather than a disruption of the existing architecture. The lift installation is no longer merely observed; it is equipped with a local diagnostic node. The device installed in the control cabinet evolves from a sensor gateway into an intelligent analysis platform capable of executing models, evaluating operating conditions, and prioritising relevant events. Existing expertise, historical data, and proven evaluation logic are leveraged to bring artificial intelligence closer to the point where technical conditions actually arise within the lift installation itself.

3 AI AS AN EXTENSION OF THE EXPERT SYSTEM – NOT A REPLACEMENT

The objective is to combine traditional expert systems with learning-based approaches. An expert system explicitly represents engineering knowledge through thresholds, plausibility checks, known fault patterns, condition classes, and experience-based decision trees. Such rules are transparent, auditable, and well established within safety-related environments.

Artificial intelligence complements this knowledge by identifying patterns that cannot easily be expressed through deterministic rules. Examples include subtle signal variations, combinations of multiple weak indicators, or installation-specific developments occurring over extended periods of operation.

A particularly interesting aspect for Edge AI systems is that the expert system can also contribute to the labelling process. Within real-world lift data, clearly defined and manually verified fault labels are relatively rare. Many events are ambiguous, occur with significant delay, or are only assessed during maintenance activities. Indirect labelling utilises existing rules, maintenance records, threshold violations, service reports, and recurring patterns to generate training data with sufficient explanatory value. Labels are therefore not created solely through manual annotation, but through the correlation of multiple technical indicators.

In this context, AI should not be viewed as a mysterious black box. Rather, it represents a second layer of analysis built upon an already well-established engineering foundation. The expert system provides structure, plausibility, and explainable intermediate states, while neural networks contribute pattern recognition, generalisation, and probabilistic assessment. The result is a hybrid diagnostic concept that applies rule-based methods where rules are effective and learning-based methods where patterns become too complex for conventional approaches.

4 HYBRID EVALUATION THROUGH A PUSH/PULL ARCHITECTURE

Edge AI does not replace the cloud. Its strength lies in an effective distribution of responsibilities. Time-critical and repetitive analyses are performed locally on the monitoring device, including preprocessing, feature extraction, condition classification, anomaly detection, and event prioritisation.

The cloud continues to perform tasks that benefit from extensive computational resources, long-term data availability, and a fleet-wide perspective. These include model training, cross-installation comparison, validation, model deployment, and long-term trend analysis.

This results in a push/pull ecosystem. Devices do not continuously transmit large volumes of raw data. Instead, they selectively provide condensed information, unusual signal sequences, model metrics, and event correlations to the cloud. The cloud pushes improved models, configurations, or adaptation modules back to suitable device classes. Conversely, devices may pull updated models whenever improvements become available for a specific lift type, configuration, or detected operating pattern.

The objective is not merely data transfer but the creation of a continuously learning system that generalises knowledge across the fleet while remaining capable of local action.

From a practical perspective, four key benefits can be identified:

- Reduced dependency on permanent connectivity
- Faster response to local events
- Lower communication requirements through local data reduction
- Improved scalability, as not every evaluation must be performed centrally

Particularly within the lift industry, where installations often have long service lifecycles, varying modernisation levels, and highly heterogeneous operating environments, this hybrid architecture represents a practical and scalable solution.

5 MODEL ADAPTATION WITHOUT FULL EDGE TRAINING

A particularly promising building block is Low-Rank Adaptation (LoRA), a technique for parameter-efficient model customisation. The basic concept is straightforward: instead of retraining a large pre-trained model in its entirety, only small adapter structures or low-rank weight modifications are learned.

For on-site monitoring devices, this approach is especially attractive because full model retraining or complete model adaptation would require significant memory and computational resources.

Applied to lift monitoring, the concept assumes the existence of generalised foundation models trained across many installations and lift categories. Smaller adaptations can then be introduced for specific lift types, rope or belt configurations, modernisation states, or environmental conditions without redistributing the complete model.

Even with currently available monitoring hardware, controlled cloud-assisted adapter generation combined with local inference is already feasible.

Within this architecture, the expert system provides context and boundary conditions, the cloud trains and refines foundation models, and LoRA-based adapters form the bridge between generalisation and installation-specific specialisation. This also improves the efficiency of communication channels. Not all data needs to be transferred in raw form, while relevant anomalies and operational insights can still contribute to the continuous improvement of future model generations.

The result is an ecosystem that learns from every installation without requiring every installation to be trained independently.

6 SUMMARY

The combination of expert systems, Edge AI, and cloud-based fleet learning opens new opportunities for lift monitoring. In the short term, the primary focus lies on local inference, hybrid diagnostic approaches, and NPU-accelerated evaluation. In the medium term, installation-specific specialisation and adaptive learning methods will gain importance. In the long term, a distributed diagnostic ecosystem will emerge in which every installation contributes to improving overall models while simultaneously benefiting from the knowledge gained across the entire fleet.

The next generation of lift monitoring therefore shifts significant parts of artificial intelligence from the cloud into the control cabinet. By combining expert systems, Edge AI, on-site Neural Processing Units, and cloud-supported fleet learning, a system architecture is created that is faster, more resilient, and more scalable than purely cloud-based approaches.

The presented approach demonstrates that the future of predictive maintenance does not lie in moving intelligence entirely to a single location. Instead, the greatest benefit is achieved through an intelligent division of responsibilities between cloud and edge computing.

The cloud makes the system capable of learning; Edge AI makes it capable of acting locally.

BIOGRAPHICAL DETAILS

Tim Ebeling has been employed since 2003 as head of development with Henning GmbH & Co. KG. In this capacity, he has established the R&D centre in Braunschweig (Germany). A team of employees is now working there on the development and production of electronic and measurement components for lifts.

Since 2012, the author has also been Managing Director and a shareholder. One of his particular focal points is measurement technology. Especially in this area, the author looks back on many years of experience in the development of acceleration and rope load measuring systems. The author's professional goal is to enrich the lift market with innovative lift components.

In addition to his role as a board member of the German Elevator Association (VFA), he is active in working groups of the European Lift Association (ELA) and serves on the advisory boards of LiftJournal and the Centre for Elevator Technology in Roßwein (ZFA).

Precise High-Speed Hoist Way Scanning System in Super-Tall Buildings

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Keywords: Super-tall buildings, Vibration measurements, Ride quality, Guide rails and landing door alignment, Multichannel fast data tracking

Abstract. Accurate guide rail alignment is critical for ensuring ride quality, reliability and safety in high-rise and high-speed lifts. Misalignments can occur not only post-installation but also over the system's lifespan, posing significant challenges for measurement and rectification using conventional methods, which are often time-consuming and complex.

This paper introduces a high-speed hoistway scanning system that captures precise data on essential shaft elements, including guide rails, guide rail fixations, and landing doors. By enabling rapid, detailed analysis even in the tallest buildings, the system accelerates engineering workflows. This is particularly valuable when used as an integral part of rectification work on the shaft system.

To achieve high-speed scanning, the system employs specialised multi-channel data tracking and advanced signal processing. We provide a brief overview of its structure and performance, along with case studies and measurements from landmark buildings: one that was formerly Asia's tallest building and another with a hoistway exceeding 300 meters. These examples identify and quantify common patterns of rail misalignment observed in practice, demonstrating the system's usage.

1 INTRODUCTION

This paper presents a new tool and method for analysing the alignment of hoistway equipment, particularly landing doors and guide rails.

Traditional methods are often time-consuming and have other practical limitations. It is also difficult to record hundreds of measurements and assign them accurately to their locations in the hoistway. Maintaining a clear overview of the data is essential for planning any realignment work.

- **Guide rails.** The new method is particularly useful for high-rise lifts, where long rail stacks include hundreds of fixing points and rail joints. Accurate guide rail installation directly affects car vibration levels. In super-tall buildings, lift speeds often exceed 8 m/s, and at these speeds, even small rail misalignments can cause unacceptable car vibration.

- **Landing doors.** High-rise shafts also contain many landing doors, and accurate installation is essential for reliable operation. Misalignment can cause equipment failures, emergency stops, and entrapments. Good compliance with installation tolerances can therefore significantly improve reliability and passenger safety.

Ensuring that hoistway equipment in long shafts complies with the relevant standards is demanding. As a result, misalignments are often present immediately after installation.

Misalignments, particularly in the guide rails, can also develop during lift operation. Contributing factors include high loads caused by building settlement, building sway due to earthquakes or strong winds, and lift test procedures such as mandatory safety-gear testing.

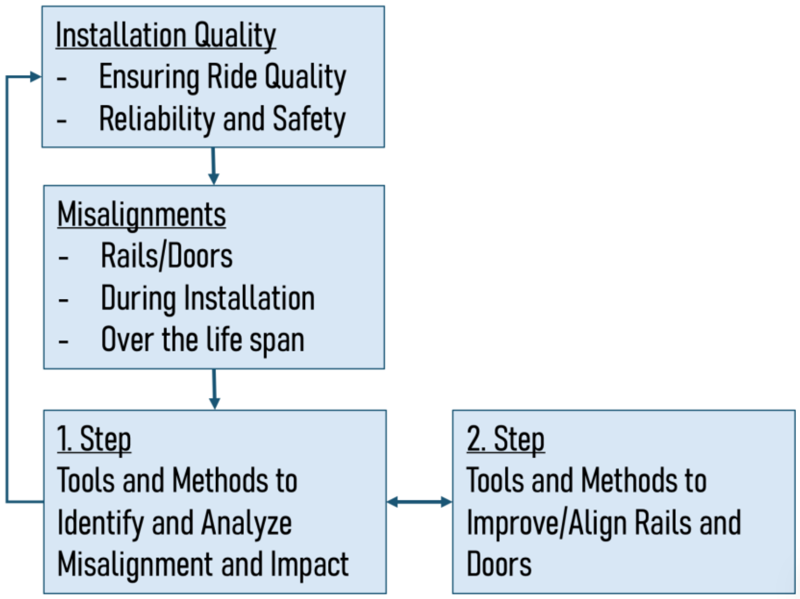

Figure 1: Overview Installation Quality- Detection and Re-Establishing

However, the focus of this paper is on the tools and methods used to identify and analyse such misalignments (Step 1) and to provide guidance for rectification work (Step 2).

The method can be applied repeatedly in a closed loop throughout the rectification process until the required alignment quality is achieved.

2 STATE OF THE ART METHODS TO ANALYSE HOISTWAY SYSTEMS AND THEIR LIMITATIONS

2.1 Conventional methods for measuring guide rail misalignment

Accurate alignment measurement of guide rails in high-rise hoistways remains a persistent challenge. In buildings exceeding 300 m, rail deviations accumulate over long travel distances, and conventional techniques struggle to deliver a sufficiently dense and reliable three-dimensional data set within acceptable downtime windows.

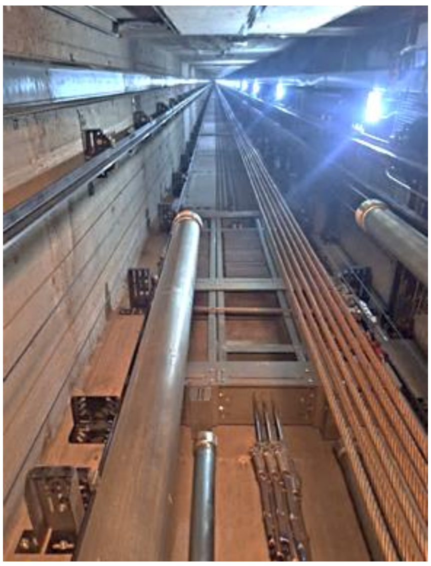

Figure 2: Lift Shaft in Hong Kong (Travel Height > 300 m)

Typical measurement scenarios involve either direct contact with the rail surfaces or optical reference lines established from the pit or machine-room level. These methods are applied sequentially, obtaining a comprehensive picture of rail straightness, bracket spacing, and door-zone geometry; often requires several hours or even days of lift shaft occupation.

2.2 State-of-the-art techniques and their practical constraints

Despite the availability of specialised instruments, current practice still relies on four principal families of methods:

Table 1: Methods to Measure Hoistway Guide Rails

#	Method	Description	Advantages	Limitation
1	Manual gauging (Distance-gauge, spirit level, angle gauge, steel ruler)	Mechanical fixtures and manual readings taken at discrete points along the rail.	Low capital cost; simple to deploy on short rises.	Extremely time-consuming; low spatial resolution; operator-dependent accuracy; no continuous plane or twist information.
2	Piano-wire tensioned reference line with displacement sensors	A taut wire is installed as a datum reference; linear sensors or dial gauges measure rail-to-wire distance.	Provides a continuous reference line.	Complex and hazardous installation; significant shaft downtime; wire sag and vibration limit accuracy in tall shafts.
3	Single-point laser or optical plum-fixtures	A laser beam or optical plummet is projected vertically; offsets are recorded at selected landings.	Rapid setup for spot checks.	Only discrete points captured; beam divergence and air turbulence degrade results over long distances; no simultaneous multi-parameter acquisition.
4	Proprietary elevator-company systems (e.g., laser tool)	Motorised trolleys carrying laser sensors or inclinometers that travel along the rails.	Semi-automated data logging; better repeatability than purely manual methods.	Still requires physical contact rollers; limited to rail surfaces only; data fusion with door or bracket information is manual and slow.

Literature on hoistway guide rail measurement is largely limited to internal manufacturer reports.

While laser-tracking or photogrammetric approaches have been proposed in isolated studies, none have reached widespread field deployment for complete guide rail shaft mapping.

Yang et al. [6] and Roberts [9] demonstrated that even minor guide rail misalignments significantly influence ride quality and vibration behaviour in high-rise elevators. Chen et al. [2] and Wang et al. [11] developed laser-based straightness measurement systems, while Li et al. [4], Zhang et al. [7] and Liu et al. [8] explored inertial, vision-based and structured-light approaches.

Although these methods improve accuracy, they remain limited in speed and completeness for very tall shafts. Kim & Park [5] and Onat et al. [10] emphasised the need for rapid, multi-sensor strategies in super-tall buildings. Wang et al. [3] further highlighted the potential of high-speed, multi-channel laser scanning to overcome existing constraints.

2.3 Problem statement and motivation for a new approach

The key requirements for modern high-speed elevators in super-tall buildings lie in the rapid and reliable detection of guide rail alignment. Existing methods do not adequately meet these requirements.

They either require the lift system to be shut down for several days or provide only sporadic and incomplete measurement data, which does not allow for a comprehensive assessment of guide rail deviations or a sound basis for targeted readjustment.

A contactless, multi-channel scanning system addresses these shortcomings by satisfying three essential criteria simultaneously:

1. **Efficiency**: acquisition of a full three-dimensional shaft model within minutes, thereby minimising downtime and enabling measurements during brief maintenance windows.
2. **Accuracy and reliability**: sub-millimetre resolution maintained over several hundred metres without mechanical contact, eliminating roller wear and rail-surface artefacts.
3. **Data fusion**: simultaneous recording of guide rail geometry, bracket positions, landing-door alignments and vibration signatures on a common time and position base.

By meeting these requirements, the system not only accelerates existing alignment tasks but also opens new use cases such as periodic condition monitoring, digital-twin generation, and data-driven rectification of entire hoistway systems; applications that remain impractical with today's state-of-the-art methods.

3 A NEW APPROACH TO ANALYSE HOISTWAY SYSTEMS

3.1 Requirements

The requirements for the system following the problem statement are as follows:

- Measurement of vibrations of the lift car to analyse ride quality
- Measurement of multiple positions of the guide rails to detect horizontal misalignments (x/y-axis)
- Simultaneous measurement of the vertical position of the lift car (z-axis). (This information shall be used as reference)
- System sampling rate to allow the 10 m/s lift car speed. Measurements shall be made with nominal speed.
- Modular and easy to install sensor setup
- Measurement logging for later analysis
- Visualisation and 1st level analysis of measured data including Frequency analysis (FFT)

3.2 Design

Our mobile measurement device is named LRQA (Lift Ride Quality Analysis System) and was developed to measure ride comfort. With position-based sampling, measurement data is recorded relative to the exact horizontal position, which offers significant advantages over time-based sampling. The core uses a cDAQ module (**C**ompact **D**ata **Acq**uisition) [13].

3.3 System overview

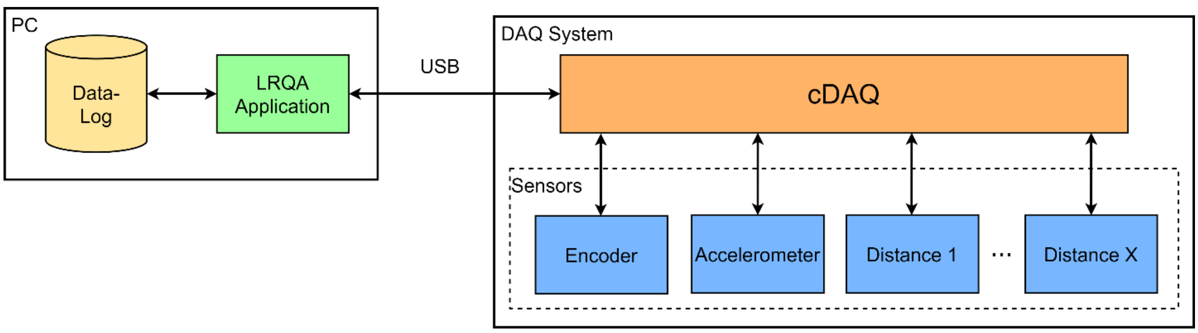

Figure 3: Block diagram of the Measurement Device LRQA

3.4 Hardware

To convert the analogue signals from the sensors, a cDAQ system was implemented. Measurement of the lift ride quality is done via different sensors. To detect the current position of the lift car, a decoder was built by utilising boreholes in the guide wheels for reference. To detect vibrations, a PI758 accelerometer [12] was used and mounted onto the lift car frame with magnets to measure the vibrations during travel.

The system has a sampling rate of 20 kHz. Because the lift speed is 10 m/s, a measurement of the rail conditions is made every 0.5 mm of distance travelled. The accelerometer has a frequency range from 0 Hz to 1.8 kHz. This means that the whole spectrum a lift passenger can perceive (from 1 Hz to 1 kHz) can be measured to analyse the ride quality. The distance sensor used for the guide rails has an accuracy of 0.01 mm and a processing delay of less than 1ms, to capture, for example, the guide rail clips with a speed of 10 m/s.

Misalignment and fixation of the guide rail are measured by using a laser distance setup. This enables the measurement of rail twisting (S1 and S2), distance between the guide rails (S3), and fixation (S4). The mechanical design is modular so it can be deployed quickly. There is a module with 4 sensors for both guide rails. The distance between the guide rails (DBG) can be calculated by adding the fixed distance of the modules to the S3 readings.

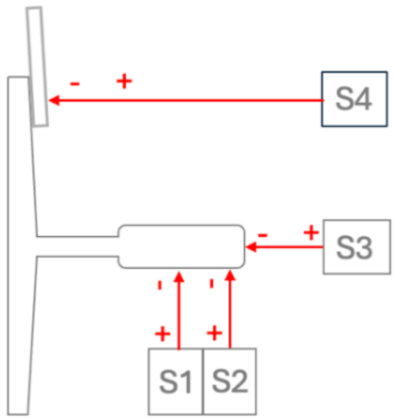

Figure 4: Sensor Setup (left guide rail)

The measurement of the misalignments and vibration in the lift car over the whole travelled distance (not over time) allows the problems with the rail that affect ride quality to be directly correlated to the vibration measurements in the analysis.

3.5 Software

The measurement sequence is controlled by a LabVIEW [13] application on a host PC that is connected to the cDAQ system via USB. Measurements are transmitted to the application, then converted and saved in a logfile. After the measurement, the logged raw data can be visualised and analysed further.

This could be expanded with further post-processing analysis, such as twisting of the rail. For the vibration measurement, raw values as well as the spectrum can be shown, see Figure 5.

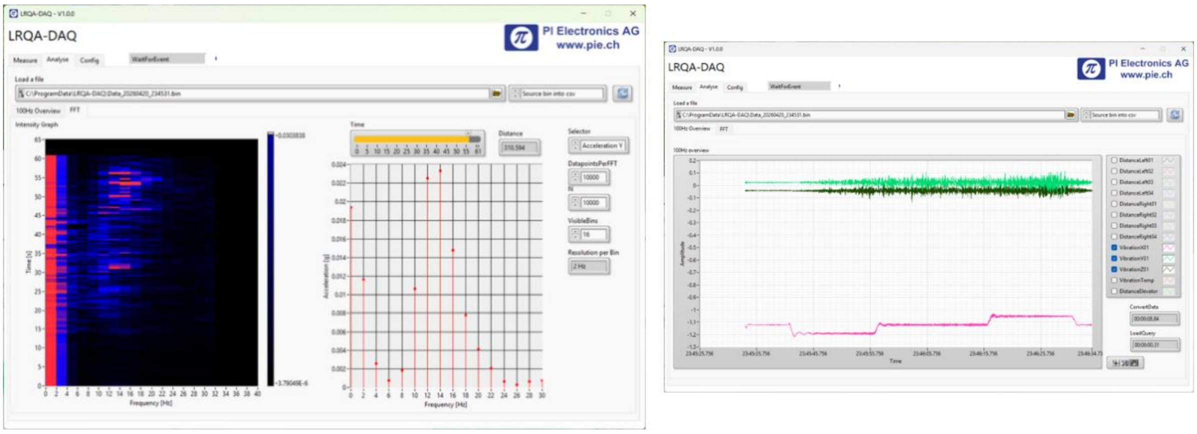

Figure 5: Visualisation of the car vibrations with the LRQA application

Time and FFT spectrum of the vibrations over the trip time can be visualised.

A map of the spectrum highlights relevant system resonances during the trip.

Above is a “real-world measurement” with a 9m/s trip in the upward direction. Intensified rope vibrations when the car approaches the top floor are visualised.

3.6 Definitions

We use the following naming and coordinates for the guide rail measurements.

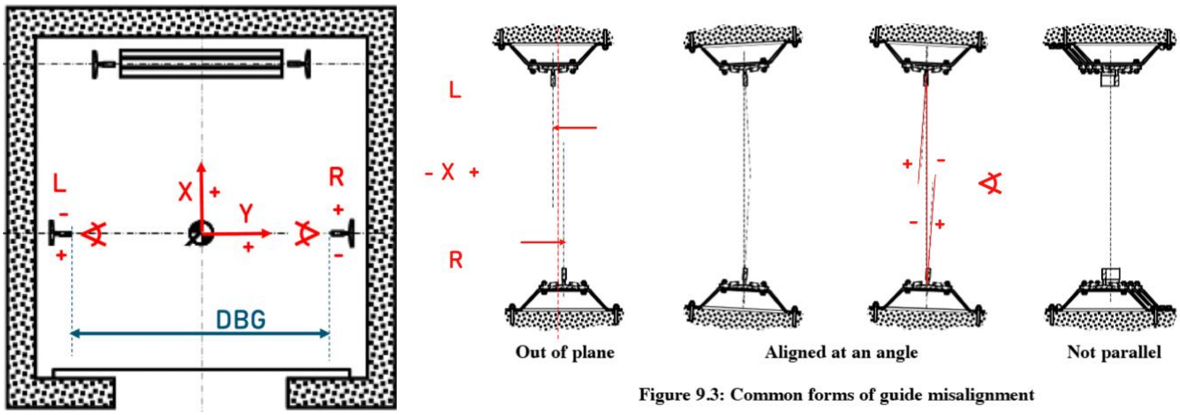

Figure 6: Coordinates and Naming of the Different Guide Rail Misalignments [1]

References are as follows:

- **Vertical:** Travel distance (Set to 0 at the beginning of the trip)
- **Horizontal:** Average of all measurements of the guide rail (x and y direction).

As an alternative, the offset to one fixed (calibrated) horizontal location can be used for each data point.

With post-processing, the sensor raw data has been scaled and translated to the understandable information of guide rail twist [degree] and “out-of-plane” [mm]. The out-of-plane value was calculated for each data point as a deviation from the average.

The distance between guide rails (DBG) is calculated as a deviation from the average.

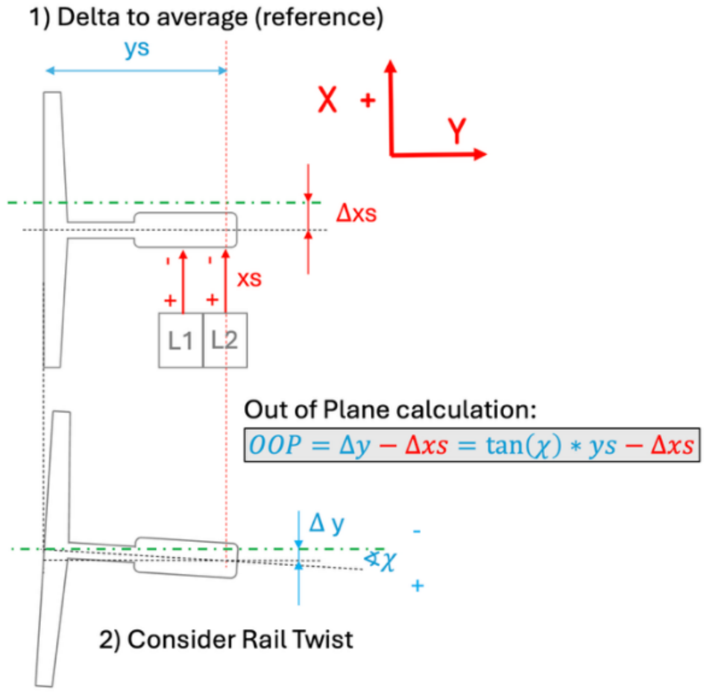

Figure 7: Out of Plane Calculation

3.7 Measurements from real installations/first findings

The device was installed and validated in two high-rise installations in Hong Kong. The selected lifts had hoist heights of 316 m and 158 m, with nominal speeds of 9 m/s and 7 m/s, respectively.

As required, data was recorded during full-speed trips in both directions. The captured data was then exported from the tool for post-processing and graph generation in Excel.

In the 2 trips in both directions, the following data was captured:

1. Car vibrations (3 axes)
2. Guide rail alignment (using 6 position sensors)
3. Guide rail fixation (using 2 position sensors)
4. Distance travelled (using the device's optical encoder)

Figure 8: LRQA- one-side sensors, recording at full speed

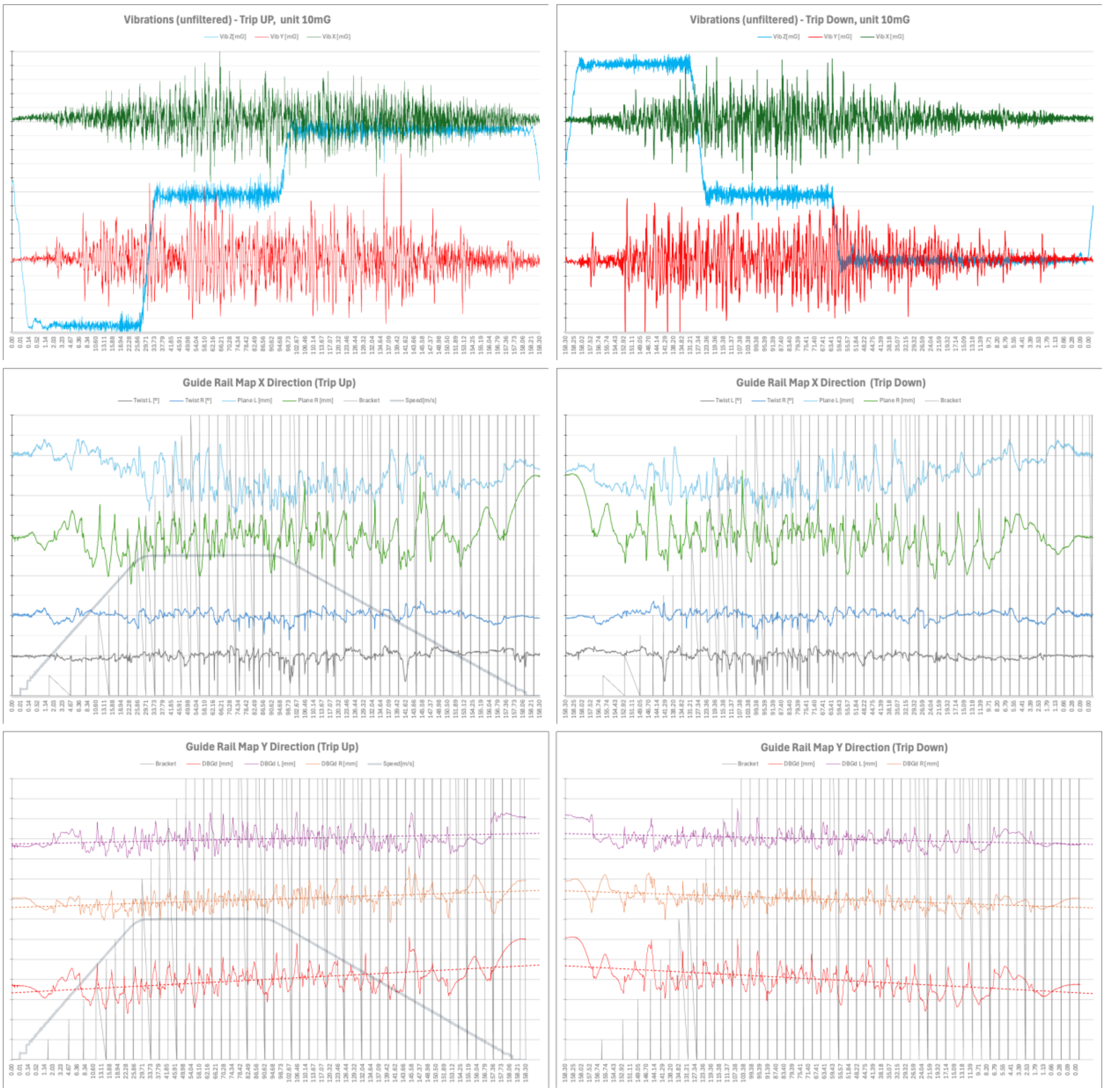

Figure 9: Record of Full Shaft, Vibration and Guide Rail Maps

The full shaft view gives an overview of the data. It helps to validate the data plausibility. The guide rail maps in both directions are highly correlated, and therefore reproducible.

For further analysis, for example of the guide rail alignment, a zoom/filter into a smaller section is needed. In this example, we chose the trip in the up direction, with a range from 80 to 110m.

Typical misalignment can be visualised and quantified as follows:

1. The right guide rail is out of plane for more than 1 bracket, by 1.5mm to 2mm. The peak is at the guide rail joint (fishplate).
2. Perfect alignment (no twist at this bracket left and right guide rail).
3. 1.5-degree twist at the right guide rail.
4. 1-degree twist at the rail fixation.
5. DBG is perfect at both rail fixation points (brackets)

6. DBG is almost more than 1mm too wide at the guide rail joints (fishplate)
7. DBG is too narrow by 1mm; each guide rail is about 0.5mm offset from the reference.

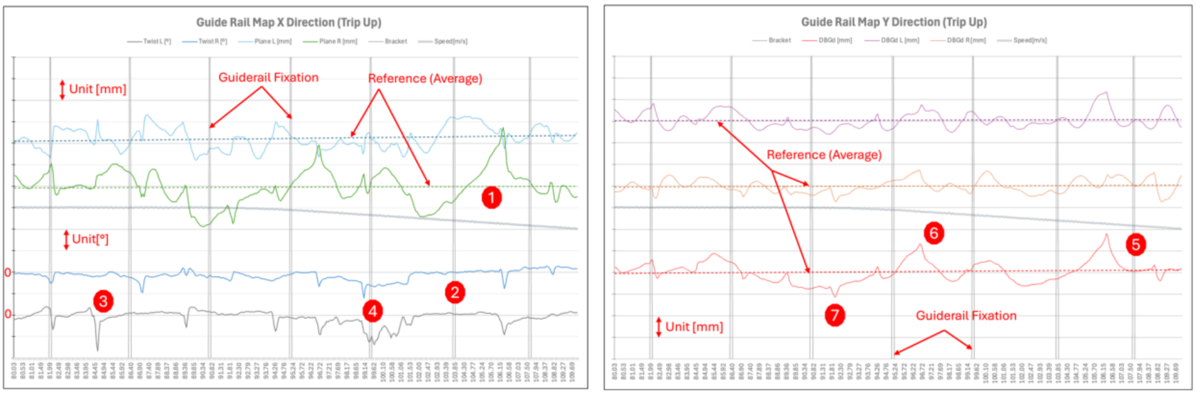

Figure 10: Guide Rail Map, Shaft Section

4 OUTLOOK: MORE USE CASES/RESEARCH

Potential future research and practical applications of the method include:

- Scanning landing door positions relative to walls or guide rails for rapid, accurate validation of installation quality.
- Scanning shaft wall accuracy.
- Combining the system with air-pressure sensors to quantify the dynamic effects of stack and piston effects.
- Combining the system with suspension-rope vibration data to assess the effect of rope vibration or uneven rope tension on ride quality.

A more compact device with remote access could also enable continuous or repeated monitoring of ride quality deterioration.

5 CONCLUSIONS

Lifts in super-tall buildings place exceptional demands on maintenance and inspection, and even brief downtime can have a major economic impact. Innovative and efficient solutions are therefore not just beneficial, but essential to sustain long-term ride quality, safety, and operational reliability.

The development of this high-speed, high-precision, contactless hoistway scanning system demonstrates the value of going beyond conventional methods.

By integrating advanced sensors, multi-channel data acquisition, and sophisticated signal processing, the system delivers comprehensive shaft analysis within minutes while maintaining the accuracy required for reliable alignment assessment and targeted rectification.

The result is possible only through close interdisciplinary collaboration across lift operations, lift engineering, and measurement/data-processing expertise.

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Michael is an Austrian lift engineer who has held leading positions in global companies. He has been working in the field of lift technology for 20 years. Michael has expertise in planning, project management and installation, as well as extensive international lift experience in Asia. In addition, he runs his own consulting office for lift technology, is a lift inspector and a certified expert witness for lift technology. Michael graduated from the University of Northampton with a degree in Lift Engineering and has extensive experience in wire ropes.

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Erich is a Swiss Engineer with more than 25 years of experience in the E&E industry in Asia and Europe.

He was a development engineer and team leader with expertise in motor control technology and was global product manager for electrical systems at a large OEM. Erich also completed an EMBA from Western University (IVEY), London, Ontario.

He found his passion to tackle complex technical and commercial topics in high-rise buildings and offers independent vertical transportation consulting services in Asia and Europe.

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Daniel is an electrical engineer with 30 years of experience in high-end measurement technology, leading a team that consistently pushes the boundaries of what is physically achievable. The team develops solutions that make the previously unmeasurable measurable - integrating complex subsystems into robust, end-to-end architectures that transform technical challenges into reliable, real-world performance. His mission is precision and robustness that give our customers a measurable competitive advantage while significantly increasing their productivity.

Theoretical Whole Building Evacuation

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Keywords: Evacuation, Evacuation Lifts, Stair Evacuation, Phased Evacuation, Operator assisted evacuation, Evacuation Capacity Assessment.

Abstract. This paper assesses the evacuation time for a 25-storey office building. The scenario modelled assumes that a fire has arbitrarily taken place at Level 11, and a whole-building evacuation is required. The evacuation will be via a phased evacuation strategy utilising the stairs for those who are able to self-evacuate, and evacuation lifts for those who are unable to self-evacuate by stairs. The stair widths have been designed to be compliant with BS 9999 recommendations. The lift evacuation strategy is operator assisted evacuation operation.

To determine the suitability of the evacuation strategy, a comparative analysis of stair evacuation times against the total lift evacuation times is undertaken.

As a base design assumption, the building is provided with two escape stair cores and one evacuation lift per escape stair core. The proportion of users who are likely to require the use of the lifts for evacuation has been taken as 15% in line with the Department for Work and Pensions family survey information.

Initial findings indicate that the estimated stair evacuation time, when calculated in line with PD 7974-6, is approximately 53 minutes, while the lift evacuation time extends to approximately 3 hours and 53 minutes. The initial calculation results indicate a significant disparity in evacuation time, which would likely raise concerns with the available evacuation lift capacity in line with the Fire Strategy requirements and other human factors.

This paper aims to explore strategies for providing lift evacuation times more in line with the stair evacuation times and enhancing overall evacuation efficiency.

1 INTRODUCTION

In recent years, evacuation lift technology has developed, and fire safety policy and guidance has started to recommend or require their inclusion in tall buildings. Clause 7.4.1 of BS 9991:2024 recommends that "buildings that are provided with passenger lift access to an upper or lower level should also be provided with a means of using lifts for escape." It goes on to recommend that "at least one evacuation lift should be provided for each escape stairway" [1].

BS EN 81-76 (Evacuation lifts) states that it is assumed that the selected number and size of evacuation lifts, as determined by a capacity assessment, is sufficient to evacuate users within the "defined duration" [2], which is explored further in this paper.

In London, the London Plan requires that buildings, regardless of height, are provided with one evacuation lift "per core" or more, subject to an evacuation lift capacity assessment [3].

These documents recommend that more lifts should be provided "if required by capacity assessment", but these documents do not provide guidance as to how this should be undertaken.

This report sets out a methodology for undertaking an evacuation capacity assessment for a fictitious office building utilising a phased evacuation.

2 BUILDING DESCRIPTION

To develop and test a methodology, a fictitious office building has been developed. A typical floorplate is indicated in Figure 1.

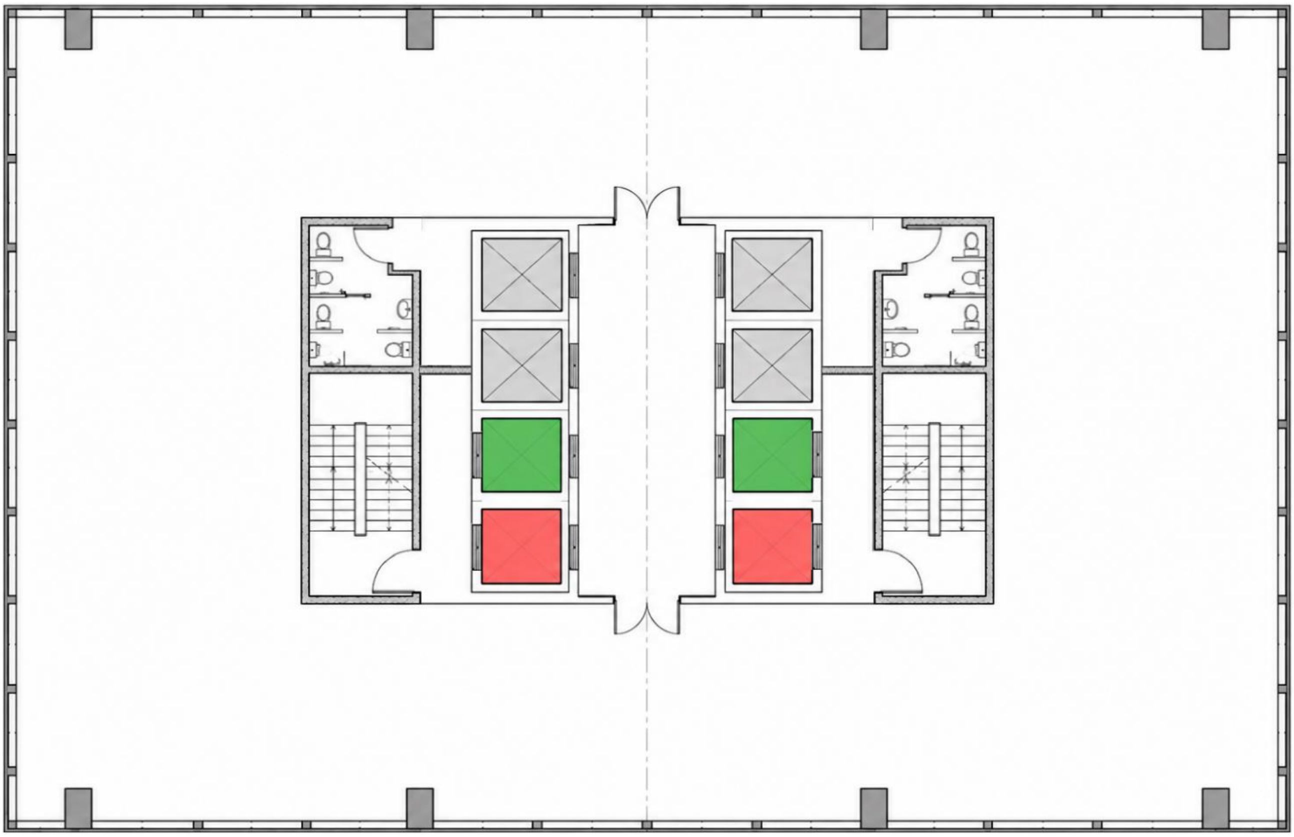

Figure 1 Typical Floor Area

The building is a 25-storey (G+24) office building, with the ground floor having independent final exits direct to outside. For simplicity, the layout (and therefore population) of the majority of floors have been kept uniform, with some exceptions to provide a more "realistic" assessment of an actual building. The baseline building population has been assessed on the maximum allowable population from the Fire Strategy requirements.

Level 1 has arbitrarily been assumed to have a 2862 m^2 NIA (excluding lifts and stairs), resulting in an occupancy of 477 (assuming 1 occupant per 6 m^2, which is typical for a "normal" office density from Table 9 of BS 9999; see Section 5.2 for a sensitivity analysis on this aspect).

Levels 2 and upwards have arbitrarily been assumed to be 2172 m^2 NIA, resulting in an occupancy of 362.

Level 24 has been assumed to have a roof garden area (assumed for the purposes of this paper to be occupied only by occupants of Level 24), reducing the NIA to 1986 m^2, resulting in an occupancy of 331.

The building has been assumed to adopt a phased evacuation regime, where the fire floor evacuates first, and evacuation then proceeds in pairs of floors going upwards, then continuing downwards in pairs below the fire floor. The ground floor will also evacuate in the first phase, but as this has exits direct to outside, this will not impact the stair or lift assessment. For this assessment, the fire has been assumed to start on Level 11.

The lift evacuation order has been assumed to follow the stair evacuation approach – i.e. evacuating Level 11 first, then continuing up the building, before evacuating users from Levels 10 downwards.

2.1 Lift provision

The two evacuation lifts in the satellite cores are provided as 2000 kg / 26 person lifts, operating at 3.0 m/s, serving Ground (G), Level 1-24 (L1-24).

The lifts are provided with a car size of 2350 mm wide x 1700 mm deep, providing an associated car area of 3.995 m^2. Door recesses are ignored and assumed to be less than 100 mm in line with the area requirements of EN 81-20.

The Evacuation Exit level (EEL) for the lifts is Ground. For the purposes of this report, it is assumed there is only one active EEL (Ground); this EEL remains free from smoke and remains safe for evacuation.

An average floor-to-floor height of 4.758 m has been utilised.

The lifts are located in a protected core area and associated with an escape stair, in line with fire guidance for location of evacuation lifts.

The lifts are specified to be provided with driver assisted evacuation operation as defined in BS EN 81-76. It is assumed that all functional requirements are met and that upon receipt of an evacuation recall signal, the lifts shall ground, landing calls will cancel, and the lifts will wait at the EEL until the driver assisted signal is operative.

Appropriate statutory signage and evacuation communication systems will be provided in compliance with BS EN 81-76.

2.2 Stair provision

Two stairs have been assumed for this assessment. A building of this height would typically require two stairs but not necessarily require a third unless needed to support travel distances, hose-laying distances, or exit capacity, which is not the case here. As shown in Figure 1, these stairs are lobbied at each level (which would be required to support the phased evacuation regime) and contain two entrances into each lobby. In the event of a fire, it is therefore not necessary to discount a stair, thus simplifying the analysis. One exit into a lobby would be discounted on the floor of fire origin to consider the effects of a fire in that location blocking an exit; however, based on there being two entries to each lobby, the other would remain available, and therefore both stairs would be accessible.

As there are two exits into the stair, the bottleneck would form within the lobby queuing into the stair, and therefore the width of the stair will govern.

Based on a sprinklered office building, and two floors evacuating at once per a phased evacuation regime, guidance in BS 9999 would recommend a total stair width of 3.40 mm/person [1]. The worst case of two adjacent floors of 477 and 362 occupants (levels 1 and 2) gives a total required width of 2852.6 mm; splitting this over two stairs gives 1426.3 mm. 2 x 1450 mm stairs have therefore been considered in the analysis.

3 METHODOLOGY

3.1 Building population analysis

Overall building population has been estimated based on typical floor space factors from Table 9 of BS 9999; see Section 2. To determine the number of users expected to rely upon evacuation lifts in the event of a fire, data from the Department for Work and Pensions (DWP) Family Resource Survey have been adopted. This states that 15% of users will be assumed to use evacuation lifts. This is split between mobility impaired, those with stamina/breathing issues/fatigue, and wheelchair users [4].

It should be noted that this is a simplistic analysis, and does not fully consider human behavioural aspects, which are discussed later.

Table 1 shows the split for the levels considered.

Table 1 Occupants expected to use evacuation lifts

Floors	Total occupancy (Baseline maximum population)	Occupants using stairs	Mobility impaired occupants	Occupants with stamina/ breathing issues/ fatigue	Wheelchair users	Total occupants per floor using lifts
1	477	406	40	29	2	71
2-23	362	308	31	22	1	54
24	331	282	28	20	1	49

3.2 Lift analysis

Due to the layout of the proposed building, and that the evacuation lifts are of the same specification, it is assumed that those who require the lifts to be evacuated will be split evenly between the lift cores. The populations presented in Table 1 have therefore been halved.

As the evacuation operation is Driver assisted, an allowance for a driver has been utilised as they will be in the lift car at all times. The driver area is 0.21 m^2. To allow for the driver within the simulations, the car area has been reduced by 0.21 m^2, providing a car area of 3.785 m^2.

The individual passenger loading times and passenger areas have been adjusted based on the specific user group who require the lifts for evacuation, which are detailed respectively in Table 2 and Table 3 below.

The capacity factor by mass has been set at 80%, and the capacity factor by area has been set at 100%.

The simulations have assumed a 5-minute shutdown period to allow queues to form at the evacuation floors. This is to simulate the operation of the lifts recalling to the active EEL, allowing for passenger to leave the car and await the driver assisted signal. Additionally, the operator and fire wardens will need to communicate with the refuge spaces. The 5-minute shutdown is arbitrary to form queues within the simulation software.

Passenger loading times have been utilised as detailed below, based on the splits presented in the DWP survey. It should be noted that the loading and unloading times require further evidence-based validation.

Table 2 Passenger Loading Times

User Group	Loading Time (s)	Unloading Time (s)
Mobility Impairment	7	7
Stamina / Breathing / Fatigue	5	5
Wheelchair Users	10	10

Passenger areas have been utilised as detailed below:

Table 3 Passenger Areas

User Group	Passenger Dimensions (mm)	Passenger Area (m^2)
Mobility Impairment	600 x 800	0.48 [5]
Stamina / Breathing / Fatigue	380 x 560	0.21 [6]
Wheelchair Users	900 x 1400	1.26 [6]

The analysis and overall results have been undertaken as per the methodology set out in Farr's paper titled "Theoretical Evaluation of Evacuation Lift Capacity Assessments" [7].

3.3 Stair analysis

To calculate evacuation time down the stairs, it is necessary to calculate flow rates based on the evacuation regime. PD 7974-6 provides flow rates for different treads and risers of stairs, ranging from 0.94-1.16 persons/s/m [8]. For this analysis, a riser of 165 mm and a tread of 305 mm have been arbitrarily assumed, giving a flow rate of 1.09 persons/s/m.

Section G.2 of PD 7974-6 notes that a "boundary layer" exists when considering flow down stairs, which considers aspects such as handrails, and to accommodate lateral body sway and assure balance. Assuming the worst case from Table G.1 of PD 7974-6 gives a boundary layer of 150 mm each side of the stair, resulting in an effective width of 1150 mm and a flow rate down the stairs of 1.2535 persons/s. As there are two stairs per level, this results in a combined flow rate of 2.507 persons/s. This has been rounded down to 2.5 persons/s for the analysis.

Flow rate calculations have been undertaken in line with the methodology in PD 7974-6. The more onerous case of a dominant upper floor has been considered (this means that occupants waiting to enter the stair will give way to occupants already in the stair and passing them). As a phased evacuation regime is in place, it has been assumed that the next phase (i.e. pair of floors) will commence evacuation as soon as the last occupant from the previous phase has entered the stair and thus left the floorplate. Additional users waiting to use the evacuation lifts have not been considered, as evacuation of all disabled users should normally commence on the sounding of the initial alert per Clause M.2 of BS 9999 (noting that the lifts in this example have followed the stair phasing as a sensible approach to prioritising those on the fire floor and higher up the building than this in line with the stair approach). This results in the values shown in Section 4.

4 RESULTS

Lift traffic simulations have been undertaken utilising the building assumptions in the preceding sections. The analysis results can be seen in Table 4.

Table 4 Evacuation Times

Level	Time taken to evacuate 15% of the floorplate population by lift (min:sec)	Time taken to evacuate 85% of the floorplate population by stair (min:sec)
11 (Fire Floor)	09:17	02:03
12-13	18:51	04:06
14-15	19:53	04:06
16-17	20:34	04:06
18-19	21:13	04:06
20-21	22:02	04:06
22-23	22:45	04:06
24	12:00	01:53
9-10	18:04	05:59
7-8	17:11	04:21
5-6	16:16	04:21
3-4	15:37	04:21
1-2	16:55	05:07
Total Time Taken	**3 hours 53 minutes 38 seconds**	**52 minutes 45 seconds**

It can be seen that the total evacuation time using the lifts is 3 hours 53 minutes. This greatly exceeds the assumed stair evacuation time of 53 minutes.

These are the times to evacuate everyone outside the building to allow a comparison between lifts and stairs; fire engineering guidance typically looks to distance/time into a stair.

5 SENSITIVITY

Sensitivity studies have been undertaken to understand how it may be possible to bring the lift evacuation time more in line with the stair evacuation time. These studies consider occupancy density and the provision of additional lifts.

The sensitivity studies are summarised as follows:

- Reduction from 15% of building users to be evacuated, to 10%. Maintaining a design occupancy of 1 person per 6 m^2.
- Reduction of the base build design criteria from 1 person per 6 m^2 to 1 person per 12.5 m^2. Maintaining 15% of the building users to be evacuated.
- Increasing the total number of lifts available for use for evacuation. Maintaining a design occupancy of 1 person per 6 m^2 with 15% of the building users to be evacuated.

5.1 Reducing the proportion of users

The base case scenario is based on each floor being occupied at 1 person per 6 m^2. The scenario also assumes that 15% of the population will require the use of the lifts for evacuation. This data is based specifically on the London Region [4].

BS EN 81-76 states that "typically at least 10% of the population has difficulties using the stairs percentage increasing as the building height increases" [2]. As a starting point, analysis has been undertaken using this 10% to determine the populations. This reduces the populations who use the lifts by 33%.

Reducing the number of people who use the lifts will increase the number using the stairs. This will have a minor negative impact on the total stair evacuation time.

Table 5 10% of Occupants expected to use evacuation lifts

Floors	Total occupancy	Occupants using stairs	Mobility impaired occupants	Occupants with stamina/ breathing issues/ fatigue	Wheelchair users	Total occupants per floor using lifts
1	477	429	27	19	1	47
2-23	362	326	20	15	0.5	35 and 36
24	331	298	19	14	1	34

5.2 Reducing the overall occupancy

The next study that has been undertaken takes into account the base build criteria. While the Fire Strategy will require 1 person per 6 m^2, the building, including vertical transportation systems, is generally designed to an effective occupancy density of 1 person per 12.5 m^2 [9]. Using the 15% from the local guidance, the populations can be determined. This reduces the populations who use the lifts by 48%.

Reducing the assumed building occupancy also means that the populations using the stairs will decrease, with an overall benefit to the stair evacuation time.

Table 6 15% of Occupants expected to use evacuation lifts with a 1:12.5 occupancy

Floors	Total occupancy	Occupants using stairs	Mobility impaired occupants	Occupants with stamina/ breathing issues/ fatigue	Wheelchair users	Total occupants per floor using lifts
1	229	195	19	14	1	34
2-23	174	147	15	11	0.5	26 and 27
24	159	135	13	10	1	24

5.3 Increasing the number of lifts

Each lift will continue to move the same number of people. Adding additional lifts will increase the overall handling capacity of the system.

Given that the lifts will all be operator-assisted evacuation lifts, even if the additional lifts are located directly adjacent to each other, they are assumed to operate as simplex lifts (not grouped). Providing eight simplex lifts will provide four times extra capacity than what is assumed within the base case.

5.4 Results of sensitivity studies

The evacuation times from the above studies are tabulated below.

Table 7 Sensitivity studies results

Option	Total Lift Evacuation Time	% change in lift evacuation time from base scenario	Total Stair Evacuation Time	% change in stair evacuation time
Base Scenario	3 hrs 53 min 38 s	-	52 min 45 s	-
10% of building occupants using the lifts	2 hrs 14 min 34 s	- 41 %	54 min 55 s	+ 4 %
Reduced building occupancy density	2 hrs 0 min 0 s	- 47 %	25 min 43 s	- 51 %
Increased number of lifts (8x simplex lifts)	54 min 31 s	-76 %	52 min 45 s	-

6 CONCLUSION AND NEXT STEPS

The results draw a simple conclusion: the fewer people there are using the lifts, the quicker the evacuation time. The more lifts there are with a stable number of people, the quicker the evacuation time. Similarly, the fewer people using the stairs, the quicker the stair evacuation time.

It is noteworthy that, if we just analysed the evacuation of the fire floor with a time of 9 minutes 17 seconds, this may be considered an acceptable solution, but evacuation times expand significantly when extending to the full building.

This building example dispels the assumption that one evacuation lift per core is automatically acceptable; it is clear that, with providing only one evacuation lift per core, the full building evacuation time by lift is several times larger than the evacuation time by stair. Reducing the proportion of users expected to use lifts in the event of a fire can significantly reduce this ratio, and the results are particularly sensitive to this aspect. The refinement of the populations who use the stairs is key, with human factors needing to be assessed. Is it possible that in a full building evacuation scenario, more people may wish to take the stairs to ensure they get out of the building? Especially given that over the years, advice has always been to not take the lifts in the event of a fire. Or conversely, will using lifts in the event of a fire become a more accepted norm, driving more people to use the lifts, perhaps including those who could manage the stairs, but with difficulty? This will likely increase for upper storeys – people will be more likely to take the stairs down two storeys than down twenty-two storeys [10]. Further research into the human factor element is critical to refine and understand the proportion of people who will use evacuation lifts, by necessity or by choice, and what will impact this decision.

However, several questions on the wider building design need to be addressed – determining how to practically implement the required number of evacuation lifts is also critical. This will necessitate an approach agreed between the members of the design team to ensure that life safety is at the core of the design, in parallel with due consideration to floorplate efficiency and capital expenditure to ensure that the building remains feasible. Currently, evacuation lifts are associated with stair cores to ensure that users can retreat to the stairs as a backup if required. Typical VT design often incorporates banks of lifts for day-to-day use, which are typically not linked to stair cores. To avoid adding more and more evacuation lifts to the stair cores to reach the eight lifts needed to "match" evacuation times, a significant shift in either fire engineering, VT engineering, or architecture with respect to evacuation lifts will be needed. This could either be a fire engineering approach to using central lift banks as evacuation lifts, without protected routes to stairs for backup, or a VT/architecture approach stepping away from a traditional central lift bank – this could include the use of a central evacuation core with multiple stairs accessible from the central lift bank. This will require multi-disciplinary collaboration to develop an efficient, optimised lift and stair layout. Similar strategies are readily specified in line with the ASME A17.1 requirements for Occupant Evacuation Operation (OEO). Could a shift in thinking allow for what is more common in some other countries?

A target evacuation time needs to be defined to determine the required number of lifts. Human factors may not allow us to leave people in the building waiting for a lift for four hours, but the construction of the building potentially could (there is a common misconception that a 2-hour fire resistance period means that the building will only last for 2 hours, whereas this is not the case. Fire resistance periods bear no relation to "real" time in a fire, and a properly designed and constructed building should be able to withstand burnout – i.e. withstand the full duration of a fire from ignition, through growth, peak, and decay). This paper has attempted, within reason, to bring the lift evacuation in line with the stair evacuation. This seems like a sensible attempt at trying to define a target, although this clearly does have a significant impact on the base building design criteria, requiring an additional 3 lifts per core in this instance (total eight provided in two cores). Standard fire safety guidance such as Approved Document B and BS 9999 have taken target evacuation times and translated these into tabulated, simplified, recommended stair widths. Consideration of whether, and how, this could be undertaken for evacuation lifts should be considered.

In summary, this paper presents a methodology for assessing the number of evacuation lifts needed to bring evacuation time in line with stair evacuation time. However, additional work is needed to determine:

- The proportion of users likely to use evacuation lifts in the event of a fire
- Guidance on determining target evacuation times
- Practical measures of providing additional evacuation lifts without unduly compromising usable floor area
- Evidence-based loading and unloading times
- Effect of method of evacuation (driver assisted or automatic)

Given the available modes of evacuation as defined in BS EN 81-76, benefits may arise from the utilisation of automatic evacuation. Whilst it is unclear at the time of writing, automatic evacuation may allow for grouping of lifts for evacuation. Allowing the lifts to operate as a group will provide benefit for overall available handling capacity. Supplementing this with driver assisted evacuation and additional evacuation lifts could lead to robust evacuation strategies.

As taller and taller buildings become more prevalent, there are some within the industry who recommend that in tall buildings, evacuation lifts should be designed to ensure a significant majority of people within the building, if not all, are able to be evacuated by the lifts. Looking at the figures presented in this report, depending on the evacuation strategy of the building, this could have a significant impact on the evacuation lift requirements.

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BIOGRAPHICAL DETAILS

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Kristian joined the lift industry as a Vertical Transportation consultant in 2020 and now works as a Senior VT Engineer for AECOM. He has worked on hundreds of projects across many sectors and countries over the years, designing VT systems.

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Designing Vertical Transportation for Modern Airports: Performance, Capacity, and Passenger-Centric Planning

Terry Lai Kin Fung

Foster + Partners

Keywords: Airport vertical transportation; Passenger flow modelling; Terminal planning; Lift and escalator design

Abstract: This paper presents a comprehensive framework for vertical transportation (VT) design in modern airports, where lifts, escalators, and moving walks form mission-critical infrastructure that directly influences passenger satisfaction, accessibility, and operational resilience. Airports are among the most demanding VT environments, required to absorb intense, scheduled surges – where a single wide-body aircraft may deliver more than 800 passengers within minutes – creating circulation pressures far exceeding those in commercial buildings.

Unlike predictable up-peak and down-peak conditions in offices, airports operate with continuously variable demand shaped by flight schedules, aircraft mix, immigration and security processing, and the growing complexity of multi-modal transfers. VT must therefore accommodate a highly diverse user group: business travellers, families with prams and heavy luggage, elderly and reduced-mobility passengers, airline crew, and staff operating across secure and landside zones.

A defining challenge is designing VT systems not just for people but for people-plus-luggage. Suitcases and trolleys consume significant car area, reduce effective capacity, slow passenger exchange, and alter flow patterns. Consequently, airport VT requires conservative loading assumptions and simulation calibrated to real passenger behaviour rather than commercial norms.

This paper emphasises the importance of early, integrated design between architects and engineers to ensure that circulation pathways, system sizing, and operational strategies are validated through reliable data and performance-based modelling. The framework incorporates airport-grade service KPIs, including waiting times, handling capacity, availability, and response targets. It also addresses accessibility and inclusivity, prioritising wide-door lift configurations, large car sizes, and alternatives such as inclined moving walks. Key resilience strategies – such as N+1 redundancy, dual power feeds, and generator backup for life-safety systems – are examined alongside sustainability measures including regenerative drives, auto-start/stop controls, and LED lighting. Finally, the paper explores digital integration, highlighting future trends such as Digital Twins and AI-optimized traffic flow.

1 INTRODUCTION

The design of vertical transportation systems for airport terminals presents a distinct set of engineering challenges that differ fundamentally from those encountered in commercial or residential buildings. Airports impose highly variable, schedule-driven demand profiles, complex circulation hierarchies, and stringent requirements for availability, safety, and resilience. In this context, VT systems function as capacity-critical infrastructure whose performance directly affects overall terminal efficiency.

However, current practice frequently treats airport VT as a downstream engineering exercise, developed after key architectural and systems-level decisions have been made. This sequential approach limits the ability of designers to optimise system capacity, redundancy, and passenger service levels, and it constrains the use of performance-based analysis during early design stages. The result is a persistent gap between theoretical handling capacity and observed operational performance.

This paper contends that early, integrated design involving VT specialists, architects, and MEP engineers is essential to closing that gap. Vertical circulation performance is strongly influenced by upstream design parameters – including level geometry, structural constraints, fire zoning, power and control strategies – that fall outside the remit of VT engineering alone. Without early interdisciplinary coordination, system performance targets such as waiting time, throughput, and recovery from disruption cannot be reliably achieved.

Importantly, early integration also enables analytical tools – such as passenger-flow simulation and demand modelling – to be used as design drivers rather than post-hoc verification tools. By applying these methods at concept and schematic stages, VT systems can be sized against explicit, airport-specific service criteria, with assumptions that reflect real passenger behaviour and operational conditions.

The research presented in this paper proposes a performance-based framework for airport VT design that embeds interdisciplinary coordination, behavioural modelling, and measurable service metrics into early project delivery. By reframing VT as a system-level engineering problem rather than an isolated equipment solution, the paper contributes to a more robust and reproducible approach to designing lifts, escalators, and moving walks for modern airport environments.

2 PLANNING PRINCIPLES & PASSENGER FLOW

Airport passenger flows are characterised by highly variable, schedule-driven demand, with arrival and departure peaks generating significant short-duration surges. Vertical transportation design shall be based on schedule-linked population modelling and discrete-event simulation of lift cores, escalators, and moving walk systems.

System performance shall target average peak waiting times of 30–40 seconds and a five-minute handling capacity of 12–15% of peak population, ensuring smooth operation during peak flight banks.

Passenger behaviour assumptions shall be incorporated into modelling:

- Airside: ~80% escalator use / ~20% lift use
- Landside: ~80% lift use / ~20% escalator use

Lift car loading factors shall be adjusted to reflect luggage-related occupancy reductions, based on average benchmarking values compiled from a range of comparable international airport projects (see Table 1).

- Airside: 40–50%
- Landside: 15–25%

Table 1 Typical Car Loading Factors – Airport Benchmarking

	CPK Airport Poland	Tocumen Airport Panama	New Phnom Penh Intl. Airport	Kuwait Intl. Airport	Average
Airside lift	~50%	~40%	~60%	~50%	~40-50%
Landside lift	~20%	~15%	~15%	~25%	~15-25%

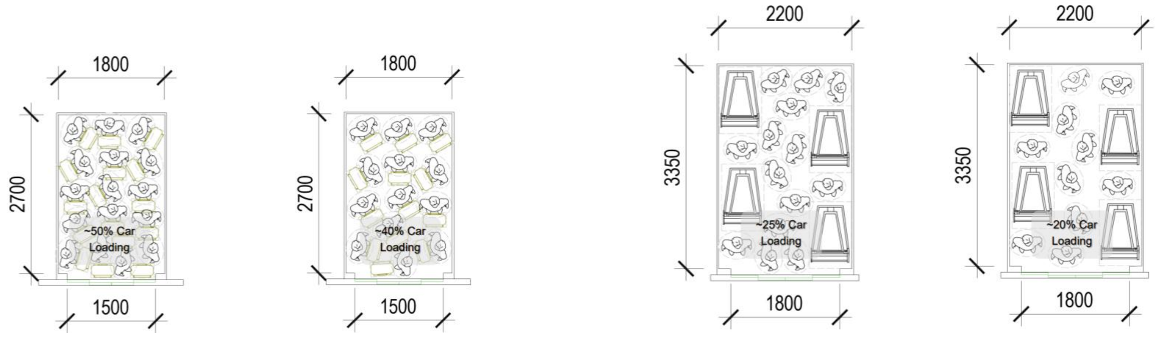

Figure 1 Typical layout of Airside lift 2500kg with 40-50% car loading factor (left) and Landside lift 4000kg with 20-25% car loading factor (right)

VT core locations shall be coordinated with architectural layouts and positioned at key decision points, with minimum ~6 m clear circulation space provided in front of lift and escalator banks to accommodate peak passenger flows.

Horizontal circulation shall be supported by moving walks (≈1400 mm pallet width, 0.65 m/s) arranged in series up to approximately 300–450 m. Longer distances shall consider automated people mover systems. Escalator provision shall be configured to suit demand, with double or triple banks in high-traffic areas.

System capacity shall be verified against five-minute demand intervals aligned with flight schedules. Design shall include segregation of landside and airside flows, accessible lift provision, and resilient power supply (e.g. dual feed with backup systems).

3 ACCESSIBILITY & INCLUSIVITY

Accessibility is a central requirement in airport design, driven by regulatory standards and shifting passenger demographics. The ageing population and increasing prevalence of passengers with reduced mobility necessitate inclusive VT systems that ensure equitable access throughout terminals.

Lifts serve as the primary vertical transport mode for passengers requiring assistance, including wheelchair users, families with strollers, and passengers with heavy baggage. Adequate cabin size (2,500–4,000 kg depending on landside/airside), door width (1,200-1,400 mm), and boarding areas (min 1.5× car depth) are critical to accommodate these needs effectively. Where feasible, dual-entrance (through-car) arrangements eliminate reversing and simplify flows for stroller and wheelchair users.

Passenger behaviour and demographic characteristics further influence the effectiveness of accessibility strategies. Escalators in infrastructure are used with some passengers standing on one side of the steps to allow others to walk and, in other cases, others standing or walking on both sides of the steps [1] [2].

Older passengers, for example, may avoid escalators due to balance concerns, while families and groups often prefer lifts to remain together during travel. In addition to fixed conveyance systems, supplementary mobility services such as wheelchairs and assist carts are frequently deployed to support passengers over long distances (see Figure 2). While these systems offer flexibility, they must be carefully managed to avoid conflicts with pedestrian flows and to minimise congestion within busy terminal areas. Ultimately, a multimodal approach that integrates various conveyance solutions is required to achieve a fully inclusive environment.

Figure 2 Autonomous Mobility Service transports passengers to their destinations and work in conjunction with a lift at Narita International Airport

4 SAFETY, RELIABILITY & REDUNDANCY

Airports demand a reliability posture closer to mission-critical infrastructure than commercial real estate. Specifications should set system availability and mean time to repair (MTTR) for priority assets, supported by remote monitoring and predictive analytics. Redundancy strategies include N+1 unit counts in critical transfer cores; Figure 3 shows an example of redundant escalator design. Dual electrical feeds with UPS and generator backup sized to run the life safety VT load – Firefighter / Evacuation lifts for ≥2 hours – and emergency features such as rescue drives that enable controlled descent to the nearest floor during power loss.

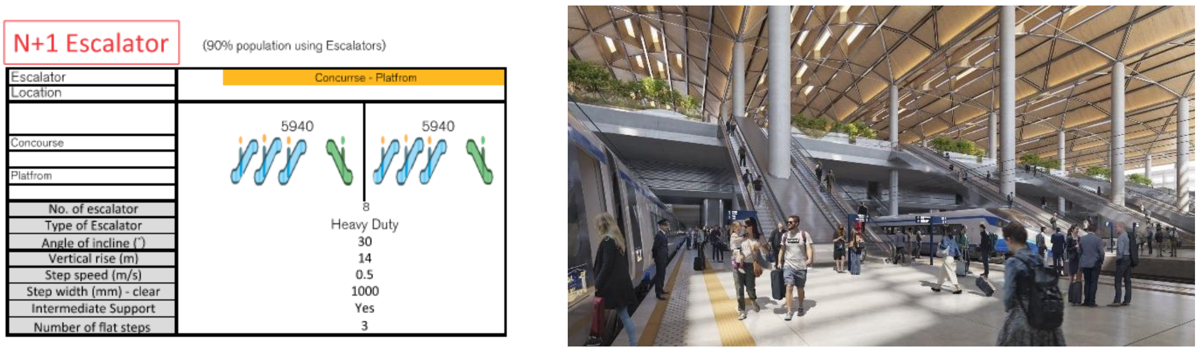

Figure 3 – N+1 Redundancy design and 3 flat steps escalator at CPK airport hub

Key safety risks include boarding and alighting incidents on escalators, falls caused by congestion or loss of balance, and misuse of equipment such as attempting to transport strollers or baggage carts on escalators. These risks are often exacerbated by unfamiliarity with the environment, highlighting the importance of both design and operational strategies to mitigate hazards. Safety bollards and 3-4 flat steps at both landings improve comfort and reduce incidents.

Reliability is equally important, as airport conveyance systems must function continuously to support uninterrupted passenger movement. Escalators, which operate constantly, are subject to higher wear and maintenance demands, whereas lifts typically operate intermittently but are more sensitive to service disruptions due to their role in accessibility. Maintenance planning must therefore account for lifecycle costs, operational uptime, and system resilience. As a result, the system must be designed with redundancy to maintain service during equipment outages and accommodate sudden surges in demand. Incorporating multiple units and designing for peak-period capacity ensures robustness and continuity of service. [3]

5 EQUIPMENT SELECTION: LIFTS, ESCALATORS & MOVING WALKS

The selection of appropriate conveyance equipment is a key determinant of system performance and must be aligned with passenger flow characteristics, spatial constraints, and operational requirements.

Lifts are indispensable for ensuring accessibility and accommodating passengers with heavy baggage, and their performance is influenced by factors such as cab size, door opening times, travel speed, and the number of stops served. Service quality is typically measured in terms of waiting time and journey efficiency, with well-designed systems achieving acceptable wait times even during peak periods.

Public passenger lifts in low-rise terminals are predominantly machine-room-less (MRL), which compacts machinery into the shaft overhead and simplifies coordination. Standardised cabin sizes and finishes (durable, vandal-resistant materials) ease procurement and lifecycle maintenance, while wide centre-opening doors (1200-1,400 mm), through-car configurations and large capacities (2,500 kg - 4,000 kg) support baggage trolley use cases.

Escalators, on the other hand, serve as the primary mode of vertical transport for most passengers due to their convenience and continuous operation. Escalators should have a 1,000 mm step width to accommodate passengers, balustrade heights around 1,100 mm for protection in open areas, 0.5 m/s speed and inclinations of 30° for comfortable boarding/alighting. The capacity is largely dependent on passenger boarding behaviour rather than theoretical throughput, with observed capacities in airport environments typically ranging between 50 and 60 passengers per minute. [4]

Moving walkways provide an effective solution for horizontal movement, particularly over long distances where walking alone would lead to fatigue and reduced passenger satisfaction. Although their impact on actual travel speed may be limited by user behaviour, they significantly improve perceived comfort and reduce the physical effort required for transit. Moving walkways reduce travel time for those who are walking/running, which helps to reduce anxiety for those in a hurry.

An effective VT strategy integrates these systems in a complementary manner, leveraging the strengths of each technology to address specific movement needs. Escalators are best suited for high-volume vertical flows, lifts for accessibility and specialised users, and moving walkways for extended horizontal connections. Table 2 summarises the typical selection criteria and key technical characteristics for lifts, escalators, and moving walkways commonly adopted in airport terminal developments.

Table 2 Summary Equipment Selection for Airport Terminals

Equipment Type	Typical Angle	Standard Width	Speed	Primary Selection Drivers
Lift	-	>1800mm	1.0-1.6 m/s	PRM compliance, heavy trolley handling, multi-level hub links
Escalator	30°	1000mm	0.5m/s	High-density inter-floor mass transit, security checkpoint feeding
Moving Walk	0° - 6°	1400mm	0.65m/s	Long concourses (>100m), passenger fatigue mitigation, speed-to-gate optimization

6 BACK-OF-HOUSE & STAFF VT STRATEGY

Unlike Front-of-House (FOH) systems, where the primary objective is to move large volumes of passengers efficiently and comfortably, Back-of-House (BOH) vertical transportation is driven by operational resilience, security segregation, and logistics efficiency. BOH lifts support a diverse range of users and cargo, including airport staff, airline crews, catering supplies, retail goods, baggage handling equipment, and oversized cargo. Consequently, lift selection is governed not only by traffic requirements but also by the physical characteristics of the transported loads, security zoning constraints, and the demanding operating environment of modern airport terminals. Typical BOH lift categories and their design characteristics are summarised in Table 3.

Table 3 – BOH Lift Type in Airport Terminals

Equipment Type	Capacity	Door Type & Width	Dimension Priority
Staff / Crew Shuttles	1600 - 2000kg	2-Panel Center Open (1100mm)	Standard wide or deep configuration
Catering & Retail Goods	2500 - 4000kg	4-Panel Center Open (1400 - 1600mm)	Deep configuration specifically dimensioned to accept standard pallet
Heavy Cargo / OOG Bags	5000 - 8000 kg	Heavy-duty vertical bi-parting or 4-Panel (>1800 mm)	Structural floor reinforcement to withstand highly concentrated wheel-point loads from motorized forklifts or heavy electric pallet jacks

In airport terminal architecture, BOH systems act as the invisible circulatory system keeping operations alive. A breakdown in BOH vertical transportation directly manifests as delayed flights, security breaches, or food service delivery failures.

The primary architectural constraint for BOH vertical transportation is the maintenance of strict regulatory borders. According to international aviation security standards, an airport terminal is divided into distinct zones that cannot cross-contaminate the public and secured areas. Staff and goods lifts must **never** inadvertently bridge a public level to a secured level without a controlled checkpoint interface.

If a BOH lift is required to physically serve both landside and airside levels, it should be configured as a dual-aspect lift with an access control system that activates landing calls and selectively enables landing door operation. In addition, BOH lifts should be integrated with the physical interlock system. When the lift doors are open, the outer security corridor doors should remain electromagnetically locked.

7 WAYFINDING & ARCHITECTURAL INTEGRATION

Wayfinding and architectural integration can significantly influence the effectiveness of vertical transportation (VT) systems. Passengers naturally follow the most visible and intuitive routes; therefore, lifts, escalators and moving walkways should be located along straightforward circulation paths with clear sightlines from key decision points. Consistent architectural treatment, including signage, lighting and finishes, further reinforces route legibility throughout the terminal.

Strategically placing moving walkways within terminal corridors can help reduce minimum connecting times and support their consistent achievement during daily operations [5]. Generous decision plazas prevent crush conditions, support trolley manoeuvres and reduce cross-flows. Avoid routing general circulation corridors directly through lift lobbies or escalator landing zones; instead, position VT slightly off the primary traffic axis with ample forecourt space, with landside/airside segregation kept legible through barriers and glazing.

Digital wayfinding should complement physical wayfinding measures. Screens located near VT facilities can display real-time flight information, walking-time estimates and gate directions, with consistent terminology repeated in the terminal app and on overhead signage visible from 25–50 m away. Visibility and signage strongly influence passenger behaviour. Clear wayfinding encourages greater use of escalators and moving walkways, while prominent lift lobbies help direct passengers with trolleys and bulky luggage towards lifts, improving both safety and passenger flow.

Figure 4 illustrates key wayfinding principles for airport terminals. Straightforward paths with unobstructed sightlines enable passengers to identify their route and destination quickly, while prominent signage helps direct passengers with bulky luggage towards lift facilities.

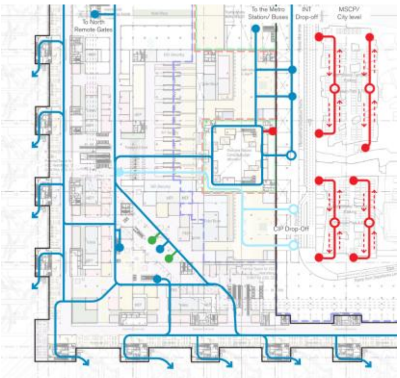

Figure 4 Straightforward paths with clear sightlines to aid airport navigation (left); Prominent signage directing passengers with bulky luggage to lifts (right).

8 DIGITAL SYSTEMS, ENERGY & SUSTAINABILITY

Modern airport VT systems are data-rich and energy-aware. Group supervisory controls integrate with Building Management Systems (BMS) and lift monitoring platforms to provide centralised alarms, telemetry and analytics, as illustrated in Figure 5 (left). Predictive maintenance uses vibration, current, door-cycle and temperature data to forecast failures and schedule interventions during off-peaks, improving availability, while remote audio/video intercoms shorten rescue times and reassure passengers during incidents.

Energy efficiency is vital for lift systems. Regenerative drives capture descent/braking energy and feed it back to the building; smart standby modes dim lighting and slow speeds when idle, potentially saving 20–30% on energy consumption [6]. Sleep-mode functionality in escalators/moving walks preserves capacity without wasting power. Combined, these features contribute to green-building objectives and measurable operational savings, especially when paired with demand-responsive strategies such as remote check-in at parking/metro that shift loads upstream and reduce terminal congestion.

Looking ahead, digital technologies will further enhance VT operations. As shown in Figure 5 (right), digital twins can model and simulate terminal operations, enabling operators to evaluate the impact of disruptions and optimise dispatch logic across lifts, escalators, moving walks and baggage systems. AI-assisted capacity planning could dynamically adjust resources in response to flight schedules, security queue lengths and gate changes, helping airports maintain efficient passenger flows under varying operating conditions [7].

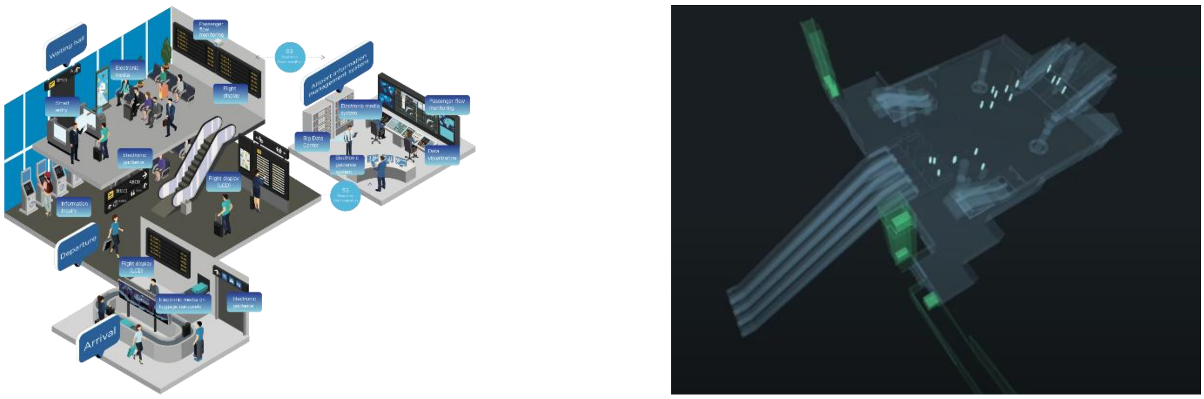

Figure 5 Examples of advanced airport VT management technologies: integrated BMS and lift monitoring platform for real-time system supervision (left); Digital twin model supporting simulation, capacity planning and operational optimisation (right).

9 CONCLUSION

This paper establishes a performance-based framework for vertical and horizontal transportation (VT/HT) design, reframing terminal conveyance from isolated equipment solutions into a system-level, mission-critical infrastructure. The intense, schedule-driven surges and the volumetric footprint of "people-plus-luggage" require a definitive departure from standard commercial design paradigms.

Peak passenger demand is typically derived from flight schedules, aircraft capacities, passenger load factors, and peak flight-bank overlaps. These profiles are assessed over five-minute intervals for VT analysis. Airport benchmarking and lift traffic planning practice indicate that a handling capacity of approximately 12–15% of the peak population within five minutes generally delivers acceptable waiting times and service levels.

To close the gap between theoretical handling capacity and real-world operational performance, VT planning must move upstream. Early architectural and engineering integration allows discrete-event simulation and demand modelling to act as design drivers rather than post-hoc verification tools. This ensures that terminal-level geometry, structural point-loading and security boundaries are optimised concurrently with equipment selection.

Looking forward, the next generation of airport terminal design will be defined by the convergence of sustainability and intelligence. Beyond the immediate energy savings provided by regenerative drives and automated standby controls, data-rich digital networks offer unprecedented operational control. By integrating smart telemetry into centralised Building Management Systems, operators can transition to predictive maintenance models that protect asset uptime. Ultimately, the deployment of predictive Digital Twins and AI-assisted capacity planning will allow terminals to dynamically recalibrate dispatch logic in real time, synchronising the terminal's physical circulation with the volatile demands of flight schedules.

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BIOGRAPHICAL DETAILS

Terry L. K. Fung is a vertical transportation specialist at Foster + Partners, London. His work focuses on the integration of lift and escalator systems within complex infrastructure, with particular emphasis on airport design for CPK Airport Warsaw and King Salman International Airport Riyadh.

He has extensive professional experience in Hong Kong, including involvement in Third Runway System of Hong Kong International Airport, contributing to the development of large-scale aviation infrastructure and passenger-focused design solutions.

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CAN vs. Ethernet in Lift Systems

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Keywords: CAN bus, Ethernet, communication, network, lift systems, elevator systems, dispatcher, traffic control

Abstract. Modern lift control systems rely on communication networks to connect numerous components, including controllers, sensors, inverters, door drives, user interfaces, and monitoring units. Controller Area Network (CAN) bus remains a widely used and well-proven standard in lift applications, valued for its robustness and predictable behaviour. However, as lift systems increasingly require higher bandwidth and closer integration with IP-based services, Ethernet is being adopted more widely. Drawing on practical experience in the design and implementation of lift control systems, this paper compares the two technologies in terms of their architectural characteristics, network topologies, scalability, communication protocols, and suitability for different parts of the system architecture.

1 INTRODUCTION

Modern lift control systems rely on communication networks to connect many components. These include controllers, sensors, inverters, door drives, user interfaces, and monitoring systems. Each of these components has different requirements for data transmission.

Therefore, communication technologies differ in their properties and performance. Important parameters include bandwidth, real-time capability, latency, number of nodes, maximum cable length, scalability, network topology, signalling methods, and electromagnetic compatibility (EMC) robustness.

These characteristics are mainly defined by the lower layers (Layer 1 and Layer 2) of the OSI (Open System Interconnection) reference model [1]. On top of this, higher-level protocols provide additional functionality depending on the application.

Several digital communication technologies are used in the lift industry. These include RS-232 (e.g., for diagnostic interfaces), RS-485 [2], CAN bus [3, 4], and Ethernet. This paper focuses on CAN and Ethernet, as they are widely used today. It discusses their key properties as well as recent developments, especially in the CAN domain.

It should also be noted that simple hard-wired signals are still used. Examples are door contacts or final limit switches. These signals only transmit basic states, such as on/off or open/closed. In addition, analogue transmission methods exist, for example using specific voltage or frequency levels. However, these are less common in modern systems.

2 GENERAL/BACKGROUND

2.1 OSI Layer Model

The OSI (Open Systems Interconnection) reference model structures communication systems into seven layers [1], separating application-oriented functions (layers 5–7) from transport-oriented mechanisms in the lower layers [5] (see Figure 1). Communication technologies such as CAN and Ethernet are primarily specified in the physical layer (layer 1) and the data link layer (layer 2) [6]. Layer 1 (physical layer) defines the electrical and physical aspects of transmission, including voltage levels, bit rates, transmission media, and bit timing and encoding, which describe when bits are sent and how they are represented as signals (signalling). Layer 2 (data link layer) specifies the rules for reliable data exchange over the physical medium, including frame formats, bus arbitration mechanisms, and error detection and correction.

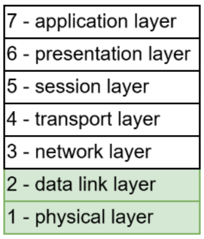

Figure 1 OSI layer model

2.2 Twisted pairs/cables

The CAN bus and modern Ethernet use twisted pairs as a transport medium. Twisted pairs are cost-efficient and robust against electromagnetic noise, as twisting supports differential transmission with strong common-mode noise rejection and reduced EMI/RFI (electromagnetic and radio-frequency interference) coupling, thereby improving signal integrity in electrically harsh environments.

Twisted pairs have individual characteristics and properties influenced, e.g. by twisting rates [7], insulation material, geometry, symmetry and tolerances [8]. Variations in these parameters lead to changes in the impedance and its uniformity along the line. This negatively affects the network's signal quality and robustness. Using high-quality cables with the right impedance is necessary, especially in networks with higher bit rates.

Twisted-pair cables require proper termination using a resistor matched to their characteristic impedance. This avoids reflections and preserves signal integrity. Twisted pair cables for data transmission usually have 100…120 ohms impedance.

2.3 Controller Area Network (CAN)

2.4 Evolution of the CAN bus

The Controller Area Network (CAN), now known as Classical CAN (CAN CC or CAN 2.0), was developed by Robert Bosch GmbH in the mid-1980s for automotive applications [6]. Its first commercial deployment was in the Mercedes S-Class in 1990 [9]. The primary objective was to enable robust and reliable communication between distributed electronic control units (ECUs), thereby reducing system complexity, wiring effort, and overall vehicle weight.

Due to these advantages, CAN was soon adopted in other embedded system domains, including the lift industry, where it has been in use since the early 1990s [3].

Classical CAN remained the dominant standard for over 25 years until the introduction of CAN FD (Flexible Data Rate) (see Figure 2) [9]. While Classical CAN supports bitrates of up to 1 Mbit/s with a maximum payload of 8 bytes, CAN FD increases data rates to 2 Mbit/s, and up to 8 Mbit/s when using signal improvement capability (SIC) transceivers. CAN FD also extends the payload size to 64 bytes. CAN FD retains a low bitrate during arbitration while allowing higher bitrates during the data phase, preserving reliable communication over longer cable lengths.

Since 2023, products implementing the latest CAN standard, CAN XL, have become available on the market. CAN XL further extends performance by supporting data rates of up to 20 Mbit/s and payload sizes of up to 2048 bytes per frame. Moreover, it enables efficient tunnelling of Ethernet OSI level 2 frames, allowing the use of higher-layer networking protocols such as TCP/IP over CAN-based networks.

In addition, CAN XL introduces built-in security mechanisms at the OSI Layer 2, including support for confidentiality and authenticity. This advancement simplifies implementing secure communication in CAN networks by reducing the need for security protocols at higher OSI layers, such as the application layer.

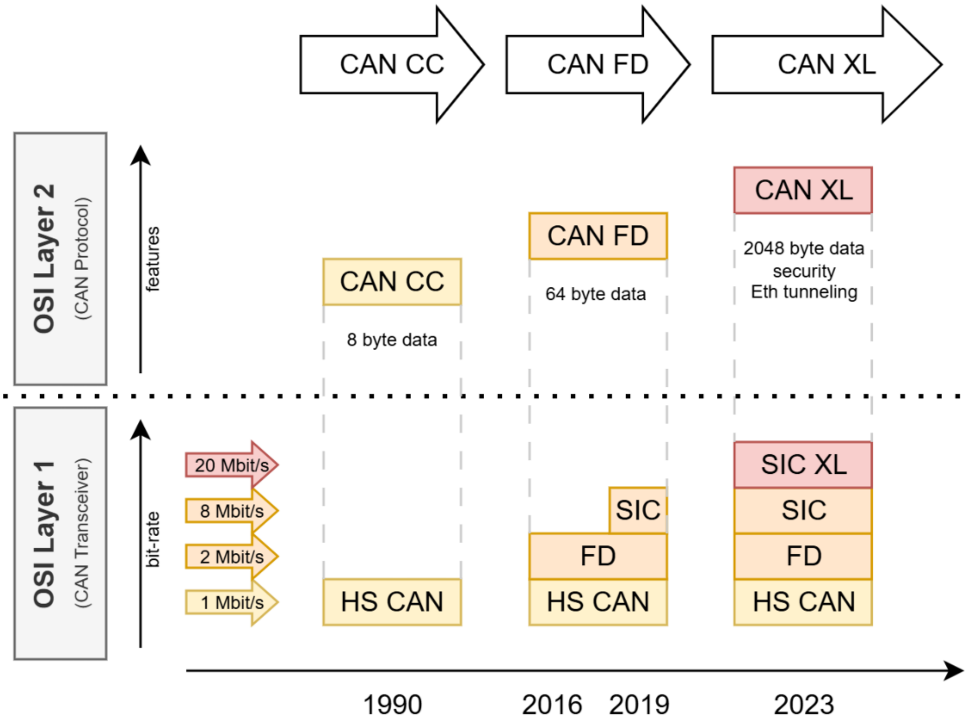

Figure 2 History of CAN standards

2.5 Network topology

The CAN bus applies a classical bus topology. Multiple nodes/devices are connected to the same wires (twisted pairs). When multiple nodes share a communication medium, arbitration mechanisms are required to prevent or resolve transmission collisions (OSI layer 2). A mechanism used by CAN is the CSMA/CR. CSMA (Carrier Sense Multiple Access) means that nodes transmit only when the medium is idle. CR (Collision Resolution) realises a non-destructive arbitration based on message priority. Simultaneous transmissions are resolved bitwise; the frame with the highest priority (lowest identifier) continues, while others abort and retry. This is an efficient bus arbitration method.

The bus topology (an example is shown in Figure 3) requires proper termination at the "main" ends of the wires (N1 and Nn). Only short stubs without additional termination resistors are allowed for additional nodes (N2…N6).

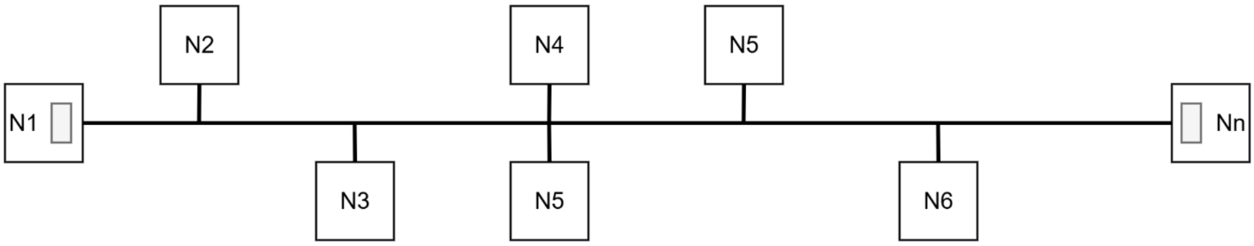

Figure 3 Bus topology

The bus cable length is limited by the arbitration bitrate. The arbitration bitrate is up to 1 Mbit/s for all CAN standards. The higher the arbitration bitrate is, the shorter the CAN bus cable must be. The maximum bus cable length, dependent on the bit rate, is shown in Table 1 [10]. With CAN FD or CAN XL, there can be a low arbitration bit rate but a high data transmission bit rate. This means that once bus arbitration is successful, CAN FD/XL can switch to higher bit rates for the data-byte transmission. The arbitration bit rate and the data transmission bitrate can be configured in CAN networks.

Table 1 CAN - Max cable length

Arbitration bit rate	Max cable length
1 Mbit/s	25m
800 kbit/s	50m
500 kbit/s	100m
250 kbit/s	250m
125 kbit/s	500m
50 kbit/s	1000m

If classical CAN nodes use new transceivers, CAN CC, CAN FD and CAN XL can be used on the same CAN bus (as long as CAN XL operates <=8 Mbit/s).

2.6 Wires

The CAN transceivers are optimised for a cable impedance of 100-120 Ohms (CAN CC and CAN FD). CAN XL is optimised for 100 Ohms. That requires twisted-pair cables of the same impedance, and likewise the bus termination. Mostly, CAN bus cables are unshielded because transmission frequencies are relatively low and CAN frame transmission is very robust. Power over the data-twisted-pairs, like Power over Ethernet PoE, is not possible.

3 ETHERNET

3.1 Evolution of the Ethernet

Ethernet (now standardised in IEEE 802.3), dating back to the 1970s, has a longer history than the CAN bus. Originally, it focused on interconnecting personal computers (workstations) and commonly used printers as shared resources in a building/office [11], with the first specification in 1980 [12]. The system was based on a shared communication medium, a coax cable (the "Ether"). Early Ethernet used CSMA/CD (Carrier Sense Multiple Access/Collision Detection), a potentially destructive arbitration method. Nodes detect collisions during transmission, abort the transmission, and retransmit after a random backoff time. The first Ethernet had 10Mbit/s.

The Ethernet connection evolved over the years [13]. While some characteristics remained unchanged, such as frame formats on OSI layer 2, the physical layer kept evolving and expanding. The different Ethernet standards are named with the following naming convention:

<rate><BASE/BROAD>-<medium/variant>

The most common variants nowadays use twisted pairs (medium = “T”), have different bit rates, and use different signalling.

The most common variants are shown in Table 2.

Table 2 Common Ethernets standards

No	ETH variant	Wires	Signalling	Type	Max cable length
A	10Base-T	2 twisted pairs	Manchester	Point to point	~100m
B	100Base-TX	2 twisted pairs	MLT/3	Point to point	~100m
C	1000Base-T	4 twisted pairs	4D-PAM5	Point to point	~100m
D	10Base-T1L	1 twisted pair	PAM-3	Point to point	~1000m
E	10Base-T1S	1 twisted pair	DME	Multidrop (shared medium)	~15 - 25m

The point-to-point Ethernet variants mentioned above support full-duplex operation. Historically, half-duplex operation has also been possible, but it is no longer relevant. Depending on the specific Ethernet standard and data rate, Ethernet employs different signalling schemes. The signalling complexity increases to achieve the higher bit rates.

Variants A and B (using two twisted pairs) assign a dedicated transmission direction to each pair. In contrast, variants C and D use all twisted pairs bidirectionally in full-duplex mode (see Figure 4). This is enabled by echo cancellation, where the device’s own transmitted signal is removed so that only the remote signal is received.

Variants A-C usually use the same PHY (physical layer transceiver) and are used in office computers and switches (also in industrial environments) and, as a standard, in many embedded devices. 10Base-T1L, as a variant of Single Pair Ethernet (SPE), focuses on process and building automation and enables the connection of sensors to Ethernet networks, including Power over Data Line (PoDL). Special switches are necessary and available.

For longer distances, where it is not possible to have intermediate switches, e.g. the lifts’ travelling cable, Ethernet standards for fibre optics exist (e.g. 100Base-FX).

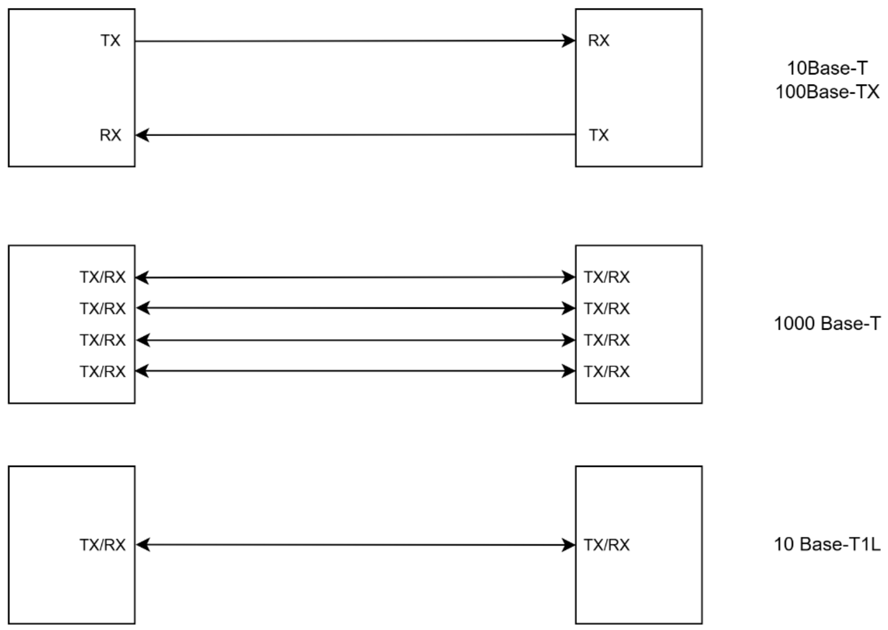

Figure 4 Ethernet full-duplex connections

3.2 Network topology

10BASE-T1S supports multidrop operation using a bus topology similar to a CAN bus (see Figure 3 above). However, it employs Physical Layer Collision Avoidance (PLCA) for bus arbitration. A central coordinator assigns transmission time slots, effectively preventing collisions. 10BASE-T1S is primarily used in the automotive industry. Due to its limited maximum cable length, it is less relevant for lift applications.

Variants A–D use point-to-point connections, so switches are required to form networks. Different concepts of network topologies exist. Their properties, advantages, and disadvantages form a field of their own, and their detailed discussion is beyond the scope of this paper.

However, some basic ideas (ring, star, tree) are shown in Figure 5 below.

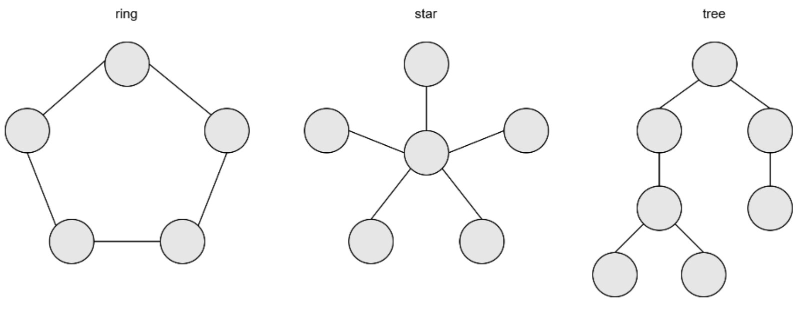

Figure 5 Ethernet network topologies (ring, star, tree)

Hybrid topologies can be used (see Figure 6) to enable efficient adaptation to application-specific requirements. With Virtual Local Area Networks (VLANs), a physical network can be divided into several virtual networks. Therefore, managed switches are necessary.

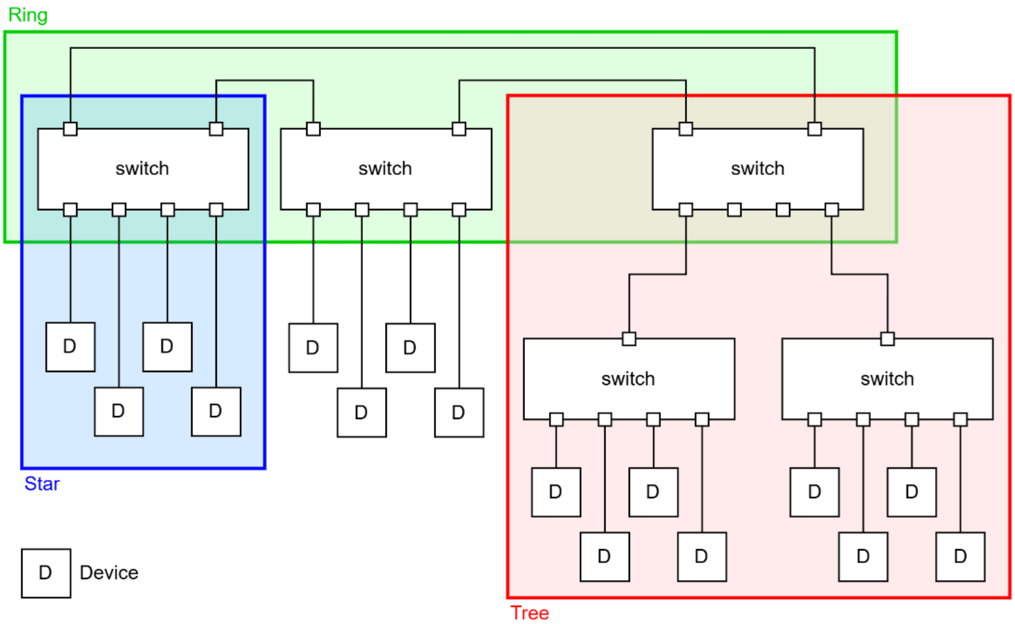

Figure 6 Ethernet hybrid network topology (example)

4 PHYSICAL ASPECTS

4.1 Wiring, EMC and signal quality

Reliable communication requires good signal quality. The higher the transmission frequency or bit rate, the more sensitive the signals become to interference. But countermeasures are possible.

One important source of interference in lift systems is electromagnetic and radio-frequency interference (EMI/RFI). The use of twisted-pair cables helps to mitigate negative impacts (see section 2.2). In applications with very high data rates or particularly harsh electromagnetic environments, shielded cables are recommended. However, interference can also originate from the system's physical design. For example, low-quality cables with large manufacturing tolerances or temperature-sensitive insulation [9] may lead to variations in the characteristic impedance. Similar issues arise from poorly designed or mismatched connectors and patch panels. Such impedance discontinuities along the transmission path can cause signal reflections and degrade overall signal integrity. Furthermore, even when high-quality components are used, improper installation practices can significantly reduce robustness. Common issues include incorrect or missing bus termination, long, untwisted "twisted" pairs, very small cable bending radius, and insufficient large-area grounding for cable shielding.

Every transition between cables through connectors introduces potential impedance discontinuities and represents a source of signal integrity degradation. Different signalling methods and bit rates result in different levels of robustness.

In the case of the CAN bus, often unshielded twisted pair cables are used. Even simple terminals are sometimes used to connect CAN cables, especially at low data rates. With its robust protocol and signalling, systems are operationally stable. With increased data rates and increased signalling complexity, good wiring and installation quality become more important.

For example, using standard terminals to connect Ethernet cables (see Figure 7) is very likely to cause issues. Using RJ45 connectors or dedicated Ethernet patch panels helps to connect, e.g. the twisted pairs of travelling cables, to the control cabinet/machine room cabling. However, especially for

Ethernet cables, it is important to keep the twisted pair twisted as long as possible. Figure 8 shows a patch panel, but with untwisted twisted pairs once they are uncovered outside the sheath/shielding.

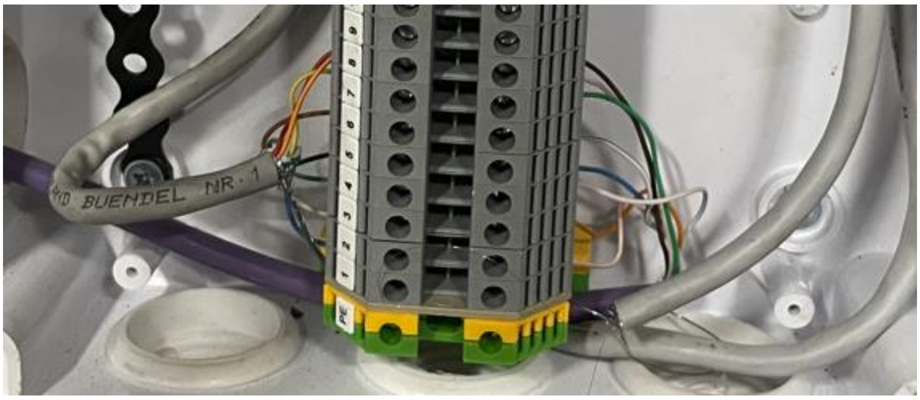

Figure 7 Ethernet connection with standard terminals

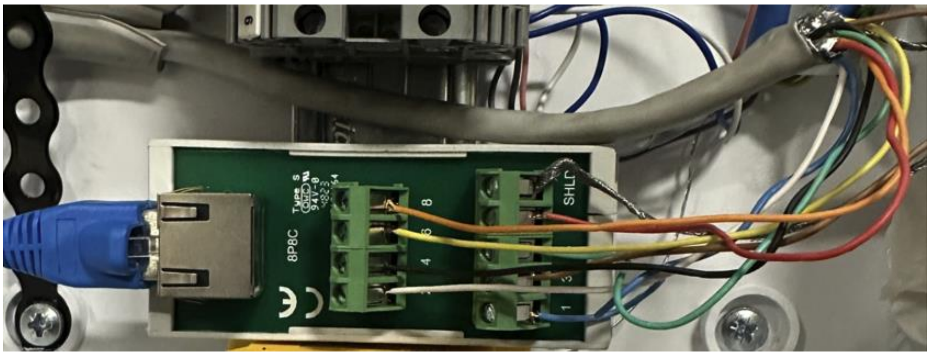

Figure 8 Ethernet patch panel with untwisted "twisted" pairs

An example of a differential CAN bus signal with an FD receiver (early generation) on a bad-terminated bus is shown in Figure 9 [14]. Reflections reduce signal quality and limit the bitrate. The logical 1 (0V) signal is ringing and oscillates beyond the threshold for a logical 0 (>0.9V). Note: New transceiver generations, such as SIC or SIC XL, improve signal quality and are more "forgiving" to poor wiring/cables, as oscillation is lower and the "signal margin" is much higher.

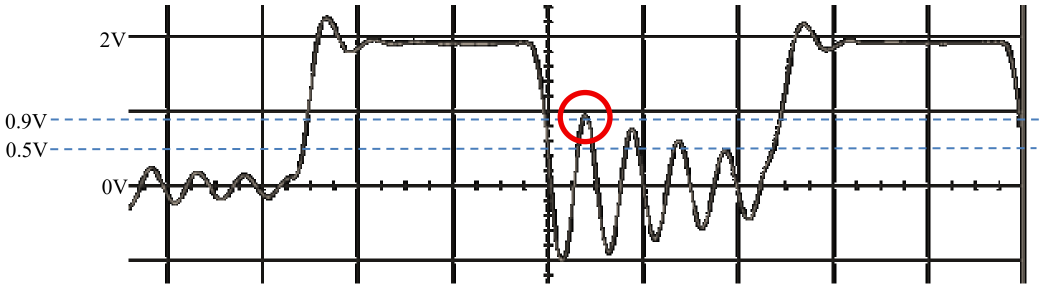

Figure 9 Ringing bus signal

This is just an example, as it is the same with other bus systems, like Ethernet. It outlines the importance of good wiring and termination.

5 DATA PROTOCOLS

Since the classical CAN bus uses simple frames, proprietary protocols at OSI level 7 running over CAN are needed. Standardised protocol definitions at OSI level 7, such as CANopen for lifts, exist [15]. CAN XL, able to tunnel Ethernet frames, make the CAN bus ready to transmit IP protocols and increases the range of applications. Ethernet, originally developed for office applications, supports network- and transport-layer protocols (TCP/IP). Plenty of OSI layer 7 protocols are available.

Internet Protocol (IP) (OSI layer 3) is an unreliable connectionless protocol that employs a best-effort delivery model. Data packets can be lost or duplicated and can be delivered in a different order than they were transmitted. Transmission Control Protocol (TCP) (OSI layer 4) builds a reliable, connection-oriented communication channel on top of IP. Data arrives in-order, duplicate packets are discarded, lost packets are re-sent, and the protocol includes mechanisms to deal with traffic congestion. To achieve this reliability, TCP gives up any guarantee of latency, and so it may not be suitable for hard real-time applications and should be used with care in soft real-time applications.

Numerous application layer protocols are built on top of TCP/IP - e.g. Domain Name System (DNS), Dynamic Host Configuration Protocol (DHCP) and Hyper Text Transfer Protocol (HTTP).

6 APPLICATION/EXAMPLE

In a lift controller system [16], multiple communication technologies are employed to interconnect components according to their specific requirements. The simplified/stripped-down example shown in Figure 10 comprises three distinct networks. An Ethernet (ETH) network connects the group controller to destination call input terminals (“kiosks”) and displays used for traffic information in the cabin. Ethernet enables these screens to operate as browser-based terminals for visualising HTTP content and receiving passenger inputs (destination calls). In addition, the lift controllers are interconnected with each other and with the group controller via a CAN network. A dedicated internal CAN bus within each lift connects components such as the lift controller, the inverter, and sensors. Only a small amount of data is exchanged over the classical CAN, but it fulfils real-time requirements.

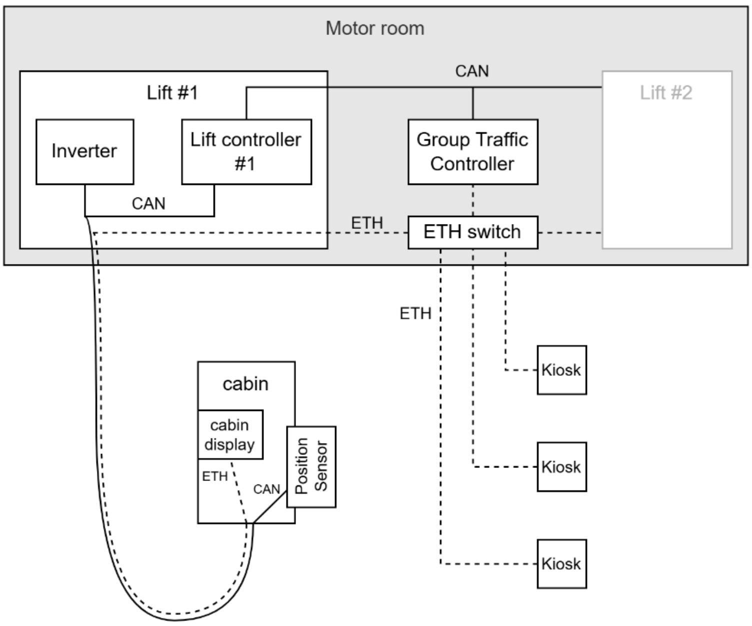

Figure 10 Simplified/stripped-down example application

7 CONCLUSION

Both CAN and Ethernet are used in lift controller networks. Both lead to stable and robust systems. However, good wiring/installation quality, along with high-quality cables and connectors, is needed, especially for higher bit rates and higher signalling complexity. The new CAN XL standard offers an option for applications that require robustness, higher data rates, and benefit from a bus topology. Additional features, such as Ethernet tunnelling and security mechanisms, help bridge the gap toward Ethernet-based communication. It will be interesting to see how Single Pair Ethernet and CAN XL will be used in future. However, Ethernet, in the context of the 10/100/1000Base-T standards, is a well-established technology for high-data-rate communication and forms the basis for IP-based networking. Moreover, many embedded components natively support the 10/100/1000Base-T Ethernet standard, resulting in the widespread availability of cost-effective off-the-shelf components.

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BIOGRAPHICAL DETAILS

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Dr Richard Peters

Richard Peters has a degree in Electrical Engineering and a Doctorate for research in Vertical Transportation. He is the CEO of Peters Research Ltd. He has been awarded Fellowship of the Institution of Engineering and Technology, the Chartered Institution of Building Services Engineers and the Society of Vertical Transportation. He is a past Chairman of the CIBSE Lifts Group. Dr Peters is the principal author of Elevate, elevator traffic analysis and simulation software.

Dr Mike Pentney

Mike Pentney has a BSc (Hons) in Electrical and Electronic Engineering and a PhD in Experimental Particle Physics. Mike worked freelance with Peters Research for about 20 years before joining as Chief Engineer in 2017. He writes software for Elevate and associated Peters Research Ltd products. He is a member of the Institute of Physics and a Chartered Physicist.

Dynamic Response of Lift Systems Under Overtravel and Buffer Impact Conditions

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Keywords: Overtravel, Buffer, Gravity Stopping Distance, Dynamic Responses, Acceleration.

Abstract. The overtravel arrest mechanism consists of buffers beneath the car and often beneath the counterweight. During lift car/counterweight buffering, both in free fall and in the scenario when the suspension remains intact, various adverse dynamic phenomena may occur and should be considered. This paper presents simplified models for predicting the dynamic behaviour of a lift system during overtravel under buffer-strike conditions. The models incorporate both linear and nonlinear buffer characteristics and are implemented in a computer simulation environment. Simulation tests are conducted over a range of buffer impact speeds and lift system parameters to evaluate buffering forces and impact-induced dynamic phenomena.

1 INTRODUCTION

There are a range of circumstances where an emergency arrest must be initiated during operation of a lift system. These include overtravel of terminal floors, either at the top or bottom of the hoistway. This may result from several factors, including failure of brake components, reduced brake friction, or the brake failing to release when de-energised; as well as traction machine failure, loss of traction, or control system malfunction.

BS EN 81-20 [1] requires lift installations to be fitted with buffers beneath both the car and the counterweight, providing a means of emergency arrest in the event of overtravel beyond the designated terminal floor. Three types of buffer are permitted: linear energy accumulation buffers, non-linear energy-accumulation buffers, and energy dissipation buffers.

Linear energy accumulation buffers consist of mechanical springs with linear characteristics, while the non-linear type consists of blocks made of polyurethane material (foam). The impact energy is stored in the form of elastic strain energy. The use of accumulation buffers is restricted to rated speeds up to 1 m/s.

For higher rated speeds, codes require that buffers dissipate the impact energy during the stopping stroke, i.e., as the buffer is compressed, so that no rebound of the car/counterweight occurs. In this case, the impact energy is dissipated rather than stored. This requirement is met by energy dissipation buffers, which are typically hydraulic (oil) in type. Such buffers can be used for lifts of all rated speeds.

2 THE DYNAMIC BEHAVIOUR

2.1 Dynamic model

Figure 1(a) shows a simplified model of a lift under buffering at the car side. Here M_1, M_2 and M_{sr} denote the masses of the car, counterweight and suspension ropes, respectively, while x_1, x_2, v_1, v_2 and a_1, a_2 represent their respective displacements, velocities, and accelerations. The diagram illustrates the car impacting the buffer, where F_b represents the buffering force. This model is subsequently used to analyse the lift dynamics and impact-induced phenomena.

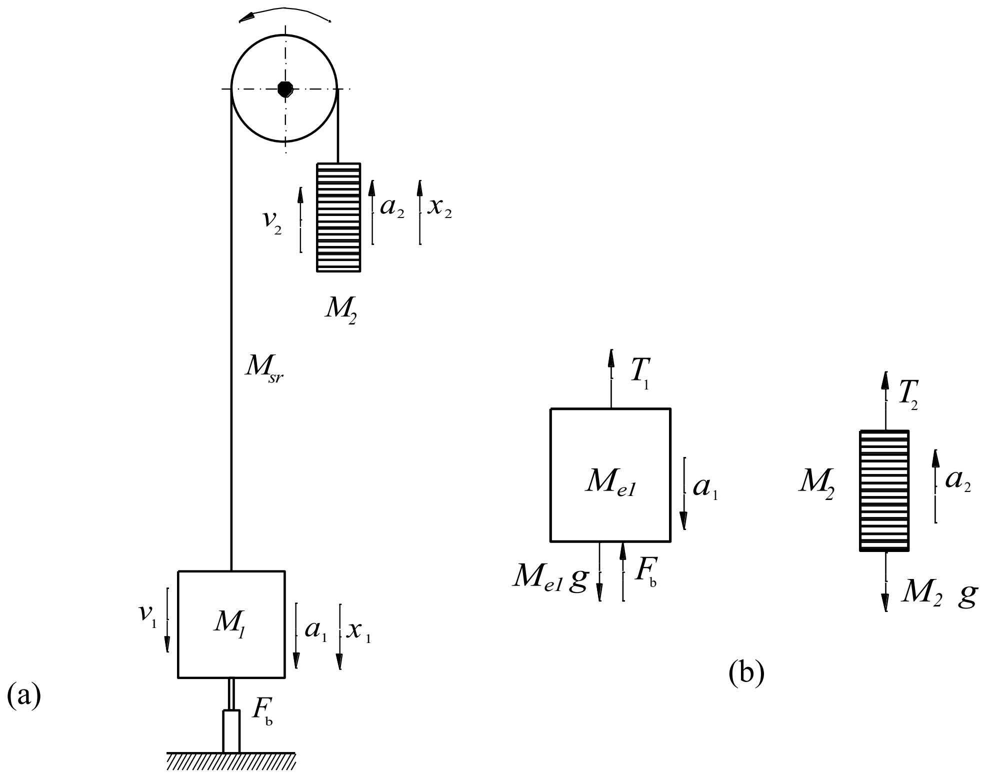

Figure 1 Lift system under buffering

Figure 1(b) shows free-body diagrams identifying the forces acting at the car and counterweight sides, respectively. Here $M_{e1} = M_1 + M_{sr}$ represents the equivalent well masses at the car side, which include the mass of suspension ropes. The mass of the short length of suspension ropes at the counterweight side is neglected in the analysis. Using Newton's second law, the balance of forces at the car and counterweight sides is given as

$$M_{e1}\ddot{x}_1 = M_{e1}g - T_1 - F_b \tag{1}$$

$$M_2\ddot{x}_2 = T_2 - M_2 g \tag{2}$$

where over dots denote the second time derivatives so that $\ddot{x}_1 = a_1$ and $\ddot{x}_2 = a_2$, T_1, T_2 represent the rope tensions at the car and counterweight sides, respectively, and g is the acceleration of gravity. Friction forces are much smaller than the buffering forces involved and are neglected in the model. Flexibility of suspension ropes is also neglected in the model given by Equations 1 - 2.

Consider a scenario when the traction drive/machine has failed, and the electromechanical brake has not engaged, resulting in a buffering event. For a low inertia machine such as a gearless lift system, the inertia of the traction machine/sheave can be neglected during the buffering stop [2], and $T_1 = T_2 = T$, $x_1 = x_2 = x$ can be used in (1) and (2). With intact suspension, the car and counterweight remain coupled (by taught ropes) when the system deceleration is no more than $1g$. The motion of the coupled system is then governed by the following equation

$$M_{eff}\ddot{x} + F_b = F_0 \tag{3}$$

where $M_{eff} = M_{e1} + M_2$ represents the effective mass of the coupled system, and $F_0 = (M_{e1} - M_2)g$.

If the deceleration is greater than 1g, the suspension ropes become slack ($T = 0$), and the equations of motion of the uncoupled system are

$$\ddot{x}_1 = g - \frac{F_b}{M_{e1}} \tag{4}$$

$$\ddot{x}_2 = -g \tag{5}$$

Equation 4 describes the motion of the car, while Equation 5 defines the motion of the counterweight, which decelerates under gravity. As it descends, the counterweight may re-engage with the suspension, causing the ropes to become taut again. During such an event, referred to as a "counterweight jump", the potential for impact loading on the ropes should be assessed [3].

2.2 Energy accumulation buffers

2.2.1 Linear spring buffers

When a linear spring buffer is compressed by a descending car, the kinetic and potential energy of the net descending mass is 'accumulated' in the compressed spring and will cause a rebound once the descending mass has been arrested. Therefore, the use of linear spring buffers is limited to low-speed installations.

EN81 stipulates that the total possible stroke of the buffers shall be at least equal to twice the gravity stopping distance corresponding to 115% of the rated speed. The minimum stroke is therefore determined as

$$s_{acc} = \frac{(1.15v)^2}{g} \tag{6}$$

In addition, it should be designed that a static load of between 2.5 and 4 times the sum of the mass of the car and its rated load should produce the stroke. This requirement is expressed by

$$(2.5 \div 4)\frac{(P+Q)g}{k} = s_{acc} \tag{7}$$

where P denotes the car mass, Q is the rated load, and k represents the spring constant. Equation 7 defines the range of spring stiffness allowed in EN81. The corresponding buffering forces in Equations 3 and 4 for the coupled system ($T > 0$) and the uncoupled car ($T = 0$) are then defined as

$$F_b = \begin{cases} kx, \ T > 0 \\ kx_1, \ T = 0 \end{cases} \tag{8}$$

respectively. The dynamic response of the coupled system defined by Equation 3 is then expressed as

$$\ddot{x} + \omega_n^2 x = f_0 \tag{9}$$

where $\omega_n = \sqrt{\frac{k}{M_{eff}}}$ and $f_0 = \frac{F_0}{M_{eff}}$. Once tension in the suspension is lost, Equation 4 describing the uncoupled response of the car is expressed as

$$\ddot{x}_1 + \omega_{1n}^2 x_1 = g \tag{10}$$

where $\omega_{1n} = \sqrt{\frac{k}{M_{e1}}}$. The counterweight ascending/descending motions are determined by Equation 5. Equations 5, 9 and 10 are linear and, with the corresponding initial conditions, can be solved analytically.

The solution of Equation 9 is defined as follows.

$$\begin{aligned} x(t) &= \frac{F_0}{k} + \left(x_0 - \frac{F_0}{k} \right) \cos \omega_n t + \frac{\dot{x}_0}{\omega_n} \sin \omega_n t \\ \dot{x}(t) &= \dot{x}_0 \cos \omega_n t - \left(x_0 - \frac{F_0}{k} \right) \omega_n \sin \omega_n t \end{aligned} \tag{11}$$

The above solution is defined over the time interval $0 \le t \le t_{f1}$, where t_{f1} denotes the time instant when tension in the suspension is lost. Considering that the initial time $t = 0$ represents the instant of the impact and the buffer is not deflected yet, the initial conditions are assumed as

$$x_0 = x(0) = 0,\ \dot{x}_0 = \dot{x}(0) = 1.15v \tag{12}$$

The solution of the equation defining the uncoupled motion of the car (10) is given as

$$\begin{aligned} x_1(t) &= \frac{M_{e1}g}{k} + \left(x_{10} - \frac{M_{e1}g}{k} \right) \cos \omega_{1n} (t - t_{f1}) + \frac{\dot{x}_{10}}{\omega_{1n}} \sin \omega_{1n} (t - t_{f1}) \\ \dot{x}_1(t) &= \dot{x}_{10} \cos \omega_{1n} (t - t_{f1}) - \left(x_{10} - \frac{M_{e1}g}{k} \right) \omega_{1n} \sin \omega_{1n} (t - t_{f1}) \end{aligned} \tag{13}$$

This solution is valid for the time interval $t_{f1} \le t \le t_f$, where t_f is the time instant when the suspension becomes tensioned again. The initial conditions that apply here are defined as $x_{10} = x(t_{f1})$, $\dot{x}_{10} = \dot{x}(t_{f1})$, respectively. On the other hand, the solution of Equation 5 over the time interval $t_{f1} \le t \le t_f$, defining the uncoupled motion of the counterweight, is determined as

$$\begin{aligned} x_2(t) &= x(t_{f1}) - \dot{x}(t_{f1}) t_{f1} - \frac{1}{2} g t_{f1}^2 + \left[\dot{x}(t_{f1}) + g t_{f1} \right] t - \frac{1}{2} g t^2 \\ \dot{x}_2(t) &= \dot{x}(t_{f1}) + g t_{f1} - g t \end{aligned} \tag{14}$$

where the initial conditions $x_{20} = x(t_{f1})$, $\dot{x}_{20} = \dot{x}(t_{f1})$ are applied. The condition for the suspension to become taut again can then be defined as

$$x_1(t_f) = x_2(t_f) \tag{15}$$

2.2.2 Non-linear buffers

Energy accumulation buffers with non-linear characteristics are required to be type-tested. EN81-20 specifies that the deceleration of a free-falling car with its rated load evaluated in accordance with EN81-50 [4] should not be more than 1g. The method of evaluation is outlined in clause 5.5.3.2.6.1 a) of EN81-50, where it is specified that the deceleration should be determined considering the time between the first two absolute minima. EN81-20 also stipulates that the deceleration peaks of more than 2.5 g should not be longer than 0.04 s (40 ms), and the maximum peak is to be limited to 6 g.

A typical force-deflection characteristic curve of a nonlinear buffer is shown in Figure 2. The curve displays non-linear and hysteretic behaviour typical for polyurethane (PU) foam materials under loading (compressing) and unloading conditions. It consists of three distinct regions: linear elastic, plateau, and steep rise. During unloading, the force is much lower in comparison with the loading (compression) phase. The hysteresis loop illustrates the capacity to absorb/dissipate energy by the buffer. The area under the loading curve represents the total energy/work input, while the area under the unloading curve represents the returned energy. The area between the two curves is the absorbed/dissipated energy by the buffer.

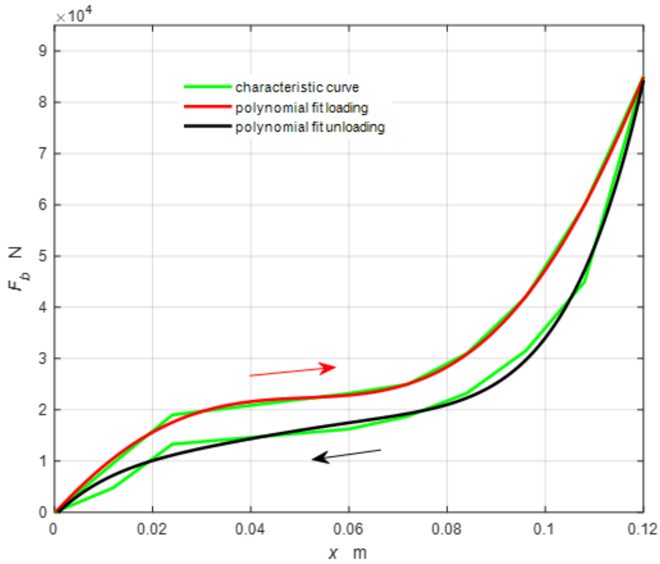

Figure 2 Non-linear buffer characteristic curve

A 5th-order polynomial can be applied to approximate the buffering force–deflection characteristic of the nonlinear buffer. The polynomial approximation is expressed by

$$F_b(x) = p_1x^5 + p_2x^4 + p_3x^3 + p_4x^2 + p_5x + p_6 \tag{16}$$

Equations 3-4 become nonlinear then, and a closed-form analytical solution cannot be readily developed. However, the system of nonlinear Equations 3-4 together with Equation 5 can be solved numerically.

2.3 Dissipation buffers

The application of energy accumulation type buffers, whether linear or non-linear, is generally limited to rated speeds below 1.0 m/s. Under some codes, the application is extended to higher speeds if there is a means of damping or 'buffering' the return movement as the car (or counterweight) rebounds from the maximum dynamic deflection [3].

At higher speeds, codes demand that the buffer should dissipate the kinetic energy during the stopping stroke, i.e. as the buffer is depressed, so that there is no rebound of the car/counterweight. This is achieved using a hydraulic buffer system.

EN81 stipulates that an energy dissipation (hydraulic) buffer is required to arrest the mass of the car with its rated load impacting the buffer in free fall with a speed of 115% of the rated speed at the average deceleration not greater than 1*g*. The minimum stroke for an energy dissipation type buffer is the gravity stopping distance corresponding to 115% rated speed. In a similar fashion to nonlinear energy accumulation buffers, the deceleration peaks of more than 2.5g should not be longer than 0.04 s.

There are various designs of hydraulic buffers [5]. In principle, the designs comprise a piston driven by the descending car (or counterweight) into a hydraulic fluid (oil). The fluid is then being transferred through restricting holes (orifices/throttles). The flow rate is a function of the orifice area [6] and is given by

$$q = C_d A_o \sqrt{\frac{2\Delta p}{\rho}} \tag{17}$$

where C_d is the coefficient of discharge, A_o denotes the orifice area, ρ represents the fluid mass density, and Δp is the pressure drop across the orifice. On the other hand, neglecting the fluid compressibility, continuity of the flow requires that

$$q = A_p v \tag{18}$$

where A_p is the piston area, and v is the speed of the piston. The pressure drop therefore is determined from Equations 17 and 18 as

$$\Delta p = \frac{\rho}{2}\left(\frac{A_p}{C_d A_o}\right)^2 v^2 \tag{19}$$

The buffering force developed due to the restriction of the hydraulic flow is determined as

$$F_{bh} = A_p \Delta p = A_p \frac{\rho}{2}\left(\frac{A_p}{C_d A_o}\right)^2 v^2 \tag{20}$$

In hydraulic buffer systems, the effective orifice flow area is not constant but varies with piston displacement due to progressive restriction of flow passages (e.g., covering of orifices or metering geometries), resulting in a nonlinear force–stroke characteristic.

With the orifice area defined as $A_o = A_o(x)$, the hydraulic buffering force is expressed as

$$F_{bh}(x, \dot{x}) = c_b(x)\dot{x}^2 \tag{21}$$

where

$$c_b(x) = A_p \frac{\rho}{2}\left(\frac{A_p}{C_d A_o(x)}\right)^2 \tag{22}$$

The buffer design includes a return spring (mechanical or gas spring). The return spring will accumulate a small fraction of the total energy to be dissipated during the buffering event. The accumulated energy is then used to return the piston to its normal extended position after the buffering operation. If the return spring's constant is denoted by *k,* the total force acting upon the car is given as

$$F_b(x, \dot{x}) = c_b(x)\dot{x}^2 + kx \tag{23}$$

The equation of motion (3) assumes the following form then

$$M_{eff}\ddot{x} + c_b(x)\dot{x}^2 + kx = F_0 \tag{24}$$

3 CASE STUDY AND EXAMPLES

In this section, the dynamic behaviour of a lift system under buffer-strike conditions is demonstrated by applying the models developed in the preceding section. Consider a lift system of rated load Q = 800 kg, comprising a car of estimated mass P = 960 kg. The travel height is H = 25 m and the counterweight is balanced at 50%. A suspension comprising four 13 mm steel wire ropes (SWR) with fibre core (FC) of mass per unit length 0.569 kg/m each is used in the installation. In the examples below, these parameters are applied to demonstrate the performance of the energy accumulation and energy dissipation buffers.

3.1 Performance example of energy accumulation buffers

3.1.1 Linear spring buffer

The analytical solutions of Equations 9-10 are defined by Equations 11 and 10, respectively. In addition, Equations 14 and 15 define the solution of Equation 5. These are applied to carry out calculations defining the buffer performance. The diagrams shown in Figure 3 illustrate the performance of a linear spring buffer for a fully loaded car of rated speed 1 m/s with suspension intact. Using Equation 6, the minimum stroke is determined as $s_{acc} = 0.1348$ m and the stiffness of the spring is selected as $k = 2.5\frac{(P+Q)g}{s_{acc}} = 3.2018\times10^5$ N/m.

The diagram in Figure 3(a) shows the displacements of the system evaluated from the instant of the car impact. The car and counterweight remain coupled until the time instant is approx. 0.11 s, when the deceleration reaches 1g (see the diagram in Figure 3(c)) and the ropes become slack. The counterweight continues its ascent, decelerating under gravity while the car is descending and then ascending on the buffer. The ascending counterweight comes to rest momentarily at the time instant of about 0.175 s and then drops back, re-engaging with the suspension at the time instant of about 0.331 s (see the area encircled in green). The speed of the counterweight when it drops back onto the suspension is 1.52 m/s as determined from the velocity diagram in Figure 3(b) (see the area encircled in green). This may impose a significant impact loading on the suspension ropes.

The car acceleration curve plotted in Figure 3(c) demonstrates that in approximately the middle of the buffering event, the deceleration exceeds 1g (however, the mean/average deceleration is less than 1g). As expected, in the region where the car deceleration is over 1g, the corresponding buffering forces reach their maximum values.

Equation 10 describing uncoupled motion of the car and its solution given by Equation 13 can also be used to predict buffering of the car in free fall. The initial conditions are then in line with Equation 12 written in the form

$$x_{10} = x_1(0) = 0,\ \dot{x}_{10} = \dot{x}_{10}(0) = 1.15v \qquad (25)$$

The solution is then defined over the time interval $0 \le t \le t_f$, so that $t_{f1} = 0$ must be substituted into Equation 13. Figure 4 illustrates the evolution of displacement, velocity, acceleration, and buffering force over this interval, with $t_f = 0.3$ s, a motion cycle like that of the intact suspension system. It is evident that the displacement, velocity, acceleration, and buffering force are all greater than those observed in the intact suspension case.

3.1.1 Non-linear buffer

The buffer characteristic presented in Figure 2 is applied in the simulation. The following coefficients are used in Equation 16 to generate the loading/unloading polynomial fits:

$$\mathbf{p}_{loading} = \left[-9.789325 \quad 2.95647 \quad -0.14916 \quad -0.01051 \quad 0.00104 \quad -0.00000022 \right] \times 10^{9}$$
$$\mathbf{p}_{unloading} = \left[2.926493 \quad -0.68354 \quad 0.06394 \quad -0.00309 \quad 0.00009 \quad -0.00000007 \right] \times 10^{10} \qquad (26)$$

The nonlinear characteristics based on coefficients in Equation 26 are then applied in a numerical solution of Equation 3. Figure 5 shows plots that demonstrate the performance of the non-linear buffer for a fully loaded car of rated speed 1 m/s with intact suspension. The car and counterweight remain coupled until a time instant of approx. 0.093 s, when the deceleration reaches 1g (as can be seen from the deceleration plot in the diagram in Figure 5(c)) and the ropes become slack. Like in the case of the linear buffer, the counterweight continues its ascent, decelerating under gravity while the car is descending and then ascending on the buffer.

The ascending counterweight comes to rest momentarily at the time instant of about 0.16 s and then drops back, re-engaging with the suspension at the time instant of about 0.286 s (see the area encircled in green). The speed of the counterweight when it drops back onto the suspension is 1.23 m/s as determined from the velocity diagram in Figure 5(b) (see the area encircled in green). The effects of the buffer hysteretic behaviour on the car deceleration can be observed in the acceleration and buffering force plots presented in Figure 5(c). The unloading phase commences after the uncoupled car displacement reaches its maximum (after the time instant of approx. 0.134 s). The buffering force then drops abruptly to a lower value (see the force vs displacement plot in Figure 7), resulting in a sudden increase in the car’s deceleration.

The evolution of displacements, velocity, acceleration and buffering forces for the car in free fall is illustrated by the plots in Figure 6, and Figure 8 shows the corresponding buffering force vs displacement plot. It is evident that the car decelerations are much higher than those with suspension intact. The peak deceleration at the time instant of about 0.12 s exceeds 2.5g. However, it can be detected that the values last no longer than 40 ms.

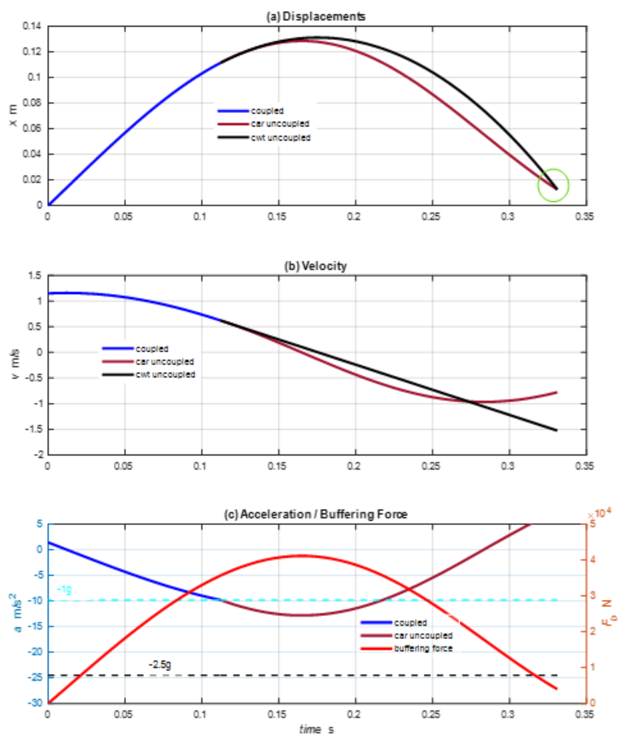

Figure 3 Linear spring accumulation buffer performance

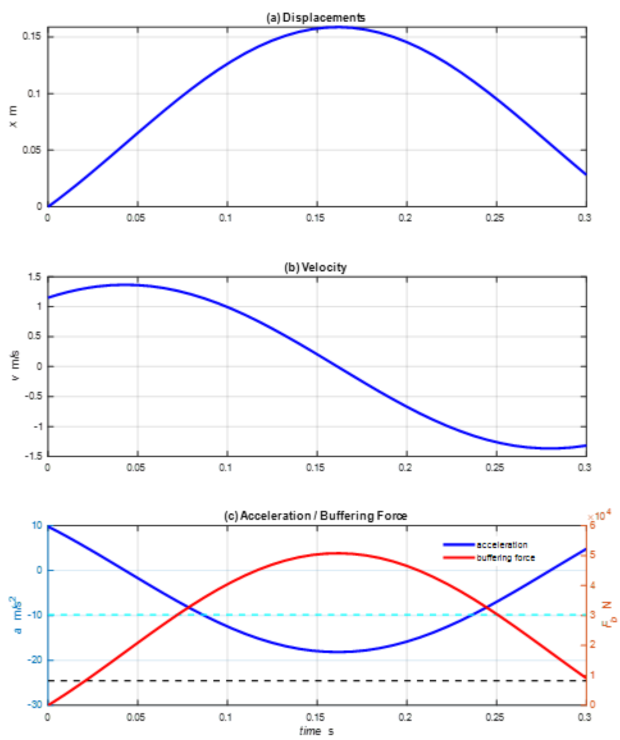

Figure 4 Linear accumulation buffer performance – car in free fall

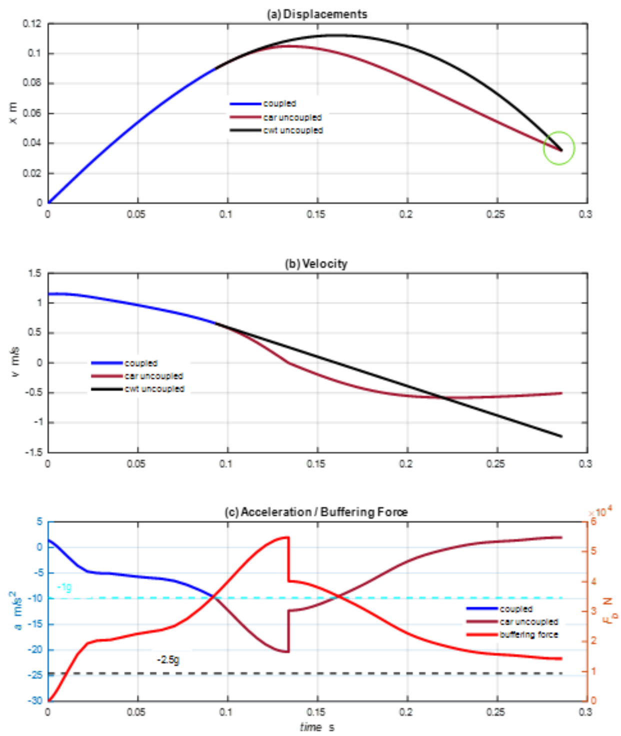

Figure 5 Non-linear accumulation buffer performance, intact suspension

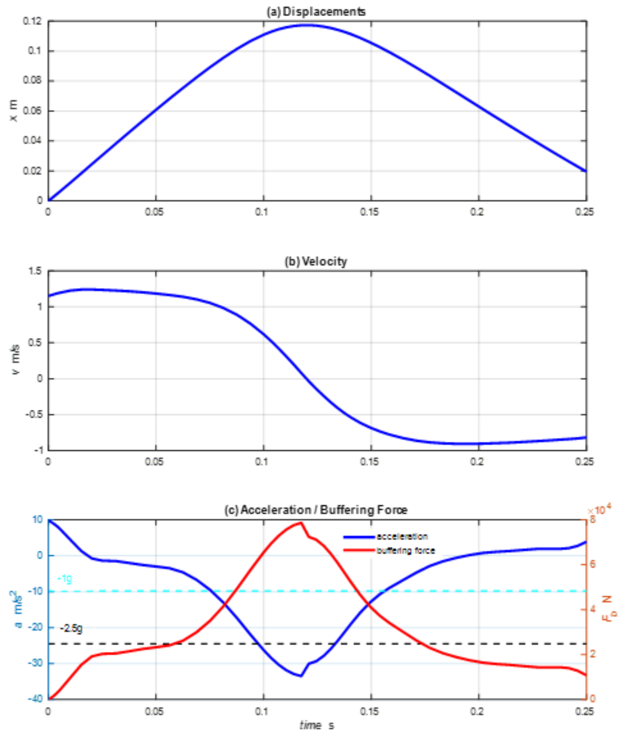

Figure 6 Non-linear accumulation buffer performance, car in free fall

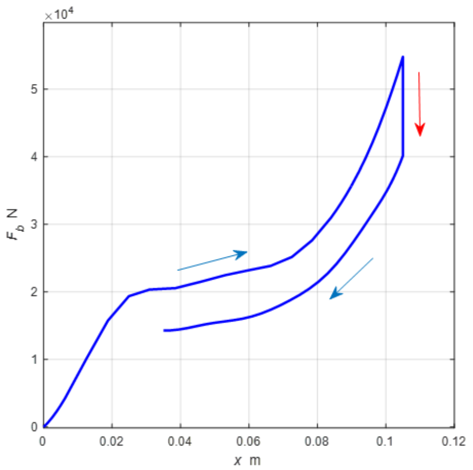

Figure 7 Non-linear buffer force vs stroke – intact suspension simulation

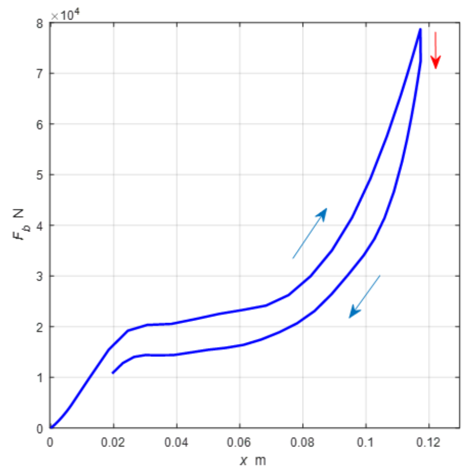

Figure 8 Non-linear buffer force vs stroke – car free fall simulation

3.2 Performance example of energy dissipation buffers

In this example, the rated speed of the lift is set to 2 m/s. A hydraulic buffer of rated speed 2.5 m/s and maximum stroke $s_{max} = 0.65$ m is used to illustrate the buffering event. The characteristic of effective orifice area versus stroke is given by Equation 27 [5].

$$A_o(x) = A_f + \sqrt{1 - \frac{x}{s_{\max}}}\left(A_{ini} - A_f\right) \tag{27}$$

In Equation 27, the initial cross-sectional area A_{ini} and final cross-sectional area A_f of the orifice are assumed as $A_{ini} = 3.0\times10^{-4}$ m^2 and $A_f = 0.05\times10^{-4}$ m^2, respectively. Figures 9 and 10 illustrate the time-dependent variation of displacement, velocity, deceleration, and buffering forces over the interval corresponding to the buffer stroke duration, for the cases of intact suspension and free fall, respectively. The results are obtained through a numerical solution of Equation 24 for the intact suspension case, while Equation 4 and Equation 23 are applied to simulate the buffering event with the car in free fall. The coefficient of discharge $C_d = 0.7$ is used in the simulation tests. As pointed out above, the return spring accumulates only a small proportion of the energy during a buffering process. The spring constant value $k = 13.3$ kN/m is assumed in the simulation, which corresponds to about 15% of the total energy of the car to be dissipated during the buffering event. Over the time interval corresponding to the buffer stroke, the deceleration of the car with intact suspension varies from about 6.4 m/s^2 at the instant of impact to 1.2 m/s^2 at the end of the buffer stroke, respectively. Thus, with the decelerations maintained below 1g, the car and counterweight remain coupled via the suspension ropes over the buffer stroke. Theoretically, a hydraulic buffer can be designed to provide a constant rate of deceleration over the length of its stroke. Considering the results shown in Figure 10, the deceleration of the car in free fall remains quite uniform, varying slightly from about 4.2 m/s^2 to 3.3 m/s^2 over the buffer stroke.

4 CONCLUSION

Simplified models for predicting the dynamic behaviour of a lift system during overtravel under buffer-strike conditions have been presented and discussed in the paper. Although the models have certain limitations – notably the neglect of rope flexibility in simulations involving intact suspension – they demonstrate the dynamic behaviour of the lift during buffering events, both with intact suspension and when the car is in free fall. In general, cases with intact suspension exhibit lower acceleration levels and reduced buffering forces compared with free-fall conditions. In addition, energy-dissipating hydraulic buffers are designed to provide more controlled deceleration, making counterweight jump phenomena less likely to occur in events where suspension remains intact.

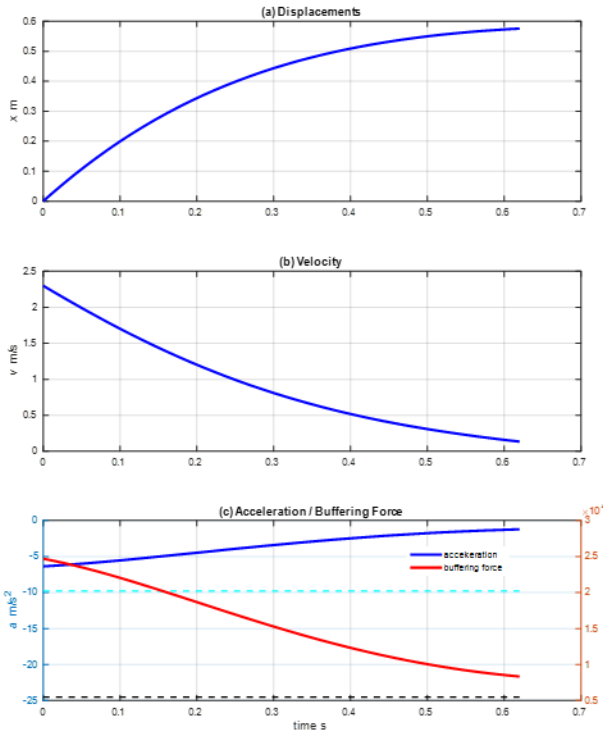

Figure 9 Energy dissipation buffer; displacements, velocity, deceleration and buffering force (intact suspension)

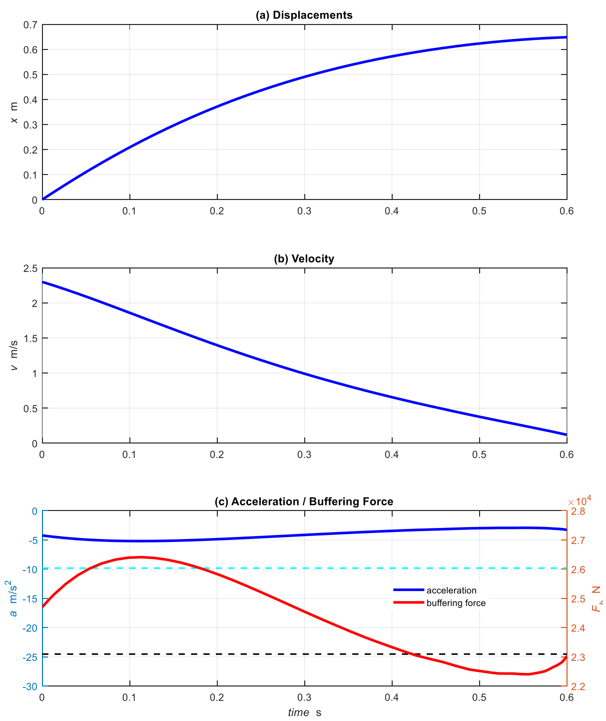

Figure 10 Energy dissipation buffer; displacements, velocity, deceleration and buffering force (free fall)

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BIOGRAPHICAL DETAILS

Professor Stefan Kaczmarczyk's expertise is in applied mechanics/ dynamics and mathematical modelling, with applications to vertical transportation systems. He has over 45 years' research and consulting experience in these areas, and he taught mechanical engineering/engineering dynamics courses at all levels. Professor Kaczmarczyk is a Chartered Engineer, a Fellow of Higher Education Academy, elected Fellow of the Institution of Mechanical Engineers and Fellow of the Society of Vertical Transportation.

Security-Oriented Artificial Intelligence-Embedded Image Processing for Lift Car Interiors

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Keywords: artificial intelligence, image processing, passenger security, car capacity.

Abstract. In lift systems, in-car cameras have become widely used for both passenger counting purposes within the cabin and for security reasons. It is known that security systems in lifts generally remain limited to basic security measures. Current applications include emergency buttons, audible warnings, and intercom use; these solutions offer a reactive approach that allows users to intervene after an event causing danger in the lift has occurred. The developed web-based interface enables the monitoring and tracking of passengers in the car, small children, pets, belongings, and potentially hazardous situations. The integration of this system with the building security system will be studied later.

1 INTRODUCTION

Lifts are indispensable components of high-rise structures, facilitating efficient vertical mobility and substantially decreasing transit time between floors. They have become an essential part of daily life, offering great convenience while also presenting certain safety risks. Their widespread adoption has also given rise to new safety concerns. Detecting the presence of humans, animals, and objects within a lift car is crucial for both lift traffic analysis and the safety of passengers and building residents. While existing literature primarily focuses on estimating passenger counts within lift cars, there is limited research regarding the detection of children, unauthorised individuals, pets, or unidentified objects.

Estimating the number of passengers within a lift car is essential for lift traffic analysis and for optimising the efficiency of lift usage within a building. Accurately estimating lift occupancy allows for the analysis of passenger flow patterns across different periods, enabling a more precise determination of the actual load range. Furthermore, monitoring car capacity serves as a preventive measure against overloading.

Conventional lifts monitor the total load capacity rather than the distribution or specific mass of individual loads. Common methods for this task include the use of load cells mounted on suspension ropes or placed under the lift car. Furthermore, excessive occupancy may compromise passenger safety and create additional hazards.

Kumar et al. [1] developed a computer system for maintaining the load balance of a lift by counting the number of people inside the lift car before operating it, in which a Haar-like algorithm was implemented. Hashimoto et al. [2] demonstrated that infrared sensors can be utilised to detect both the direction and the number of passengers entering and exiting the lift. Ma et al. [3] proposed a passenger counting approach in the lift based on channel state information (CSI) measurements using commodity Wi-Fi. Vision-based methodologies [4–8] predominantly rely on image recognition techniques for crowd estimation. Fan et al. [9] proposed a person counting methodology based on morphological outline connection area analysis, which was subsequently validated using real-world lift surveillance footage.

While other methods focus on estimating the number of passengers inside the lift car, Shen and Chu [10] deployed GPU-based edge devices in a four-story building to count individuals entering specific areas. In contrast to other studies in the literature, Al-Sharif and Barney [11] developed a mathematical approach known as the "I-S-P method" (Inverse Stops-Passengers), which infers the number of passengers in a lift car based on the number of stops made in either the upward or downward direction. Unlike the I-S-P method, this study employs an image-based methodology to facilitate accurate passenger estimation.

2 PASSENGER COUNTING TECHNOLOGIES

Passenger counting technologies – whether applied to public transit (metros, trains, buses) or lift cabins – are primarily categorised into two distinct methodologies: vision-based (image-based) and non-vision-based (sensor-based) approaches.

In recent years, non-vision-based methodologies have gained significant traction, being broadly categorised into device-based and device-free approaches [12]. Non-vision-based methodologies incorporate a diverse array of technologies, such as physical sensors, wireless radio frequency (RF), network signals, and acoustic waves to facilitate accurate occupancy estimation within a given environment. Nevertheless, these methodologies often encounter spatial limitations and demonstrate a heightened susceptibility to inaccuracies when monitoring dense pedestrian flows.

Sensor-based methodologies utilise a diverse range of sensing technologies to perform people counting. Traditional sensor-driven crowd estimation techniques, such as infrared sensors, pressure sensors, and mobile-based systems, often mandate specialised infrastructure or require proactive user participation, complicating their implementation. These requirements often prove intrusive and impede the seamless integration of such systems across diverse environments.

In contrast to sensor-based methodologies, image-based approaches provide significant advantages for occupancy detection, as they are not subject to spatial constraints and can capture comprehensive environmental data within a single frame. Video-based surveillance and image processing techniques provide a practical and non-intrusive approach to occupancy detection, achieving high levels of accuracy at a relatively low cost [13]. While image-based methods provide broader spatial coverage compared to their non-image-based counterparts, they also tend to offer superior reliability in counting accuracy. This study concerns a system that integrates artificial intelligence-based image processing and object recognition technologies.

3 DETECTION IN THE ELEVATOR

The proposed methodology is most effective in scenarios where cameras are positioned to provide a plan view of the monitored area. The challenge of occupancy estimation within lift lobbies and lift cars represents a specific case of the broader problem of object counting in complex and dynamic environments. A prerequisite for counting is the initial detection and localisation of objects within the frame. The counting process begins with the identification of individual objects as they enter the monitored area. The counting process does not necessarily depend on object recognition or precise localisation. Instead, the system must simply detect the presence of entities that do not belong to the normal background environment. The system is designed to facilitate efficient route planning, allowing users to reach their destinations via the fastest possible paths while minimising lift wait times and lobby congestion.

3.1 Monitoring and tracking in the car

The developed web interface enables the monitoring and tracking of passengers in the car, small children, pets, belongings, and potentially hazardous situations.

By utilising the developed system, precise detection can be achieved for all occupants inside the lift car, encompassing potential fall detection, smoking inside the cabin, objects that pose a danger in enclosed environments (e.g., firearms, knives, and prohibited materials), and abandoned items (such as boxes, parcels, bags, and suitcases). Additionally, real-time alerts can be transmitted to report various negative occurrences or noteworthy anomalies.

The integration of real-time data collection and visualisation allows operators to maintain constant situational awareness of the lift environment, thereby accelerating the identification of critical incidents and streamlining emergency response procedures.

3.2 System design

The proposed smart lift system is designed primarily for high-rise building applications, including high-traffic commercial and residential complexes, as well as environments where occupant safety and operational comfort are paramount. With the aim of improving safety within lift systems, camera-based image processing and artificial intelligence techniques are utilised to identify passengers, objects, animals, and ongoing events inside the lift car.

Figure 1 depicts representative configurations of the lift car utilised in the system, demonstrating the empty state, the presence of passengers and animals, and the condition containing exclusively objects.

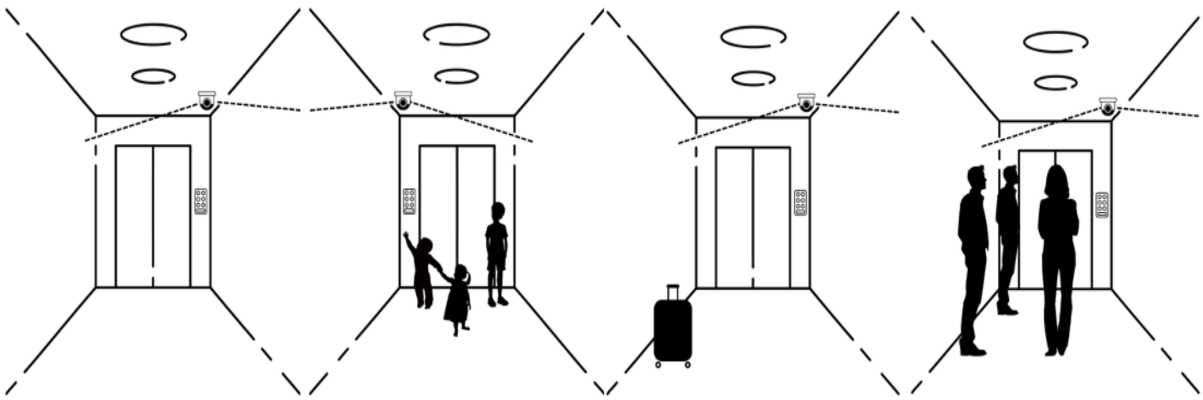

Figure 1 Lift car configuration and possible situations

The smart lift system, integrated with artificial intelligence-based image processing and object recognition technologies, comprises at least one wide-angle camera capable of operating in low-light conditions to capture real-time images within the cabin; at least one embedded computing board that processes the collected images, detects objects and individuals, analyses various scenarios, and executes at least one object recognition algorithm; at least one scalable database where all processed data is securely stored; a lift control panel to which the processed data is transmitted via a CANBUS or MODBUS communication line; and at least one web interface functioning as a management panel, enabling authorized users to monitor real-time events, review historical logs, and intervene in emergencies.

A representative schematic diagram illustrating data processing and the destination routing of emergency alerts within the lift cabin is presented in Figure 2.

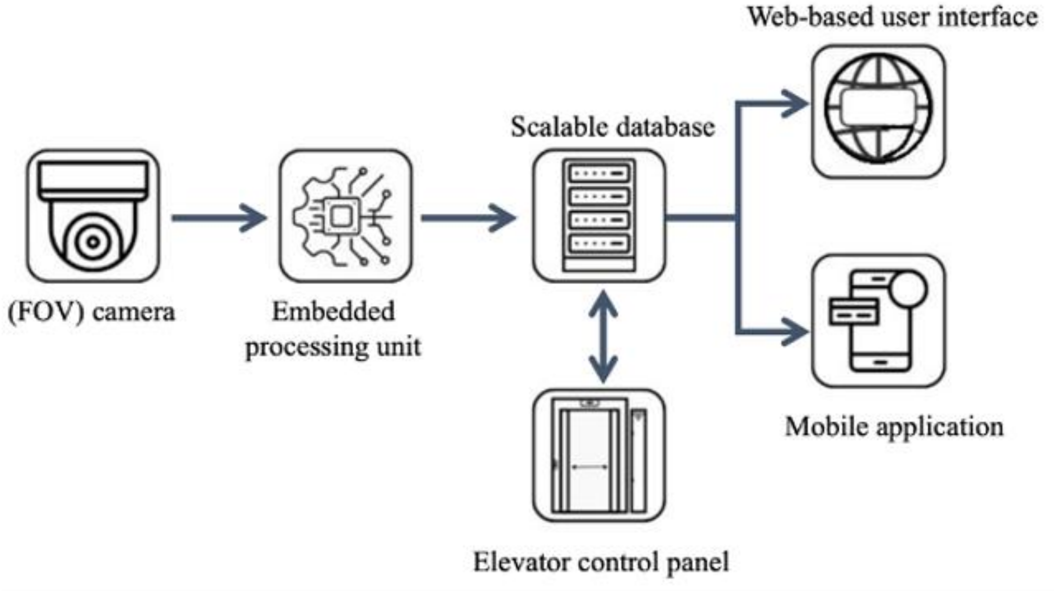

Figure 2 Representative schematic diagram of the system

A wide-field-of-view (FOV) camera with low-light capability is used for real-time image acquisition inside the lift car. The system necessitates an embedded computing board configured to handle image processing, perform human and object detection for scenario analysis, and run the designated object recognition models. A scalable database is integrated into the architecture to ensure the secure storage and efficient management of all processed logs. Within the system configuration, a web-based graphical user interface (GUI) is integrated to allow authorised personnel to track live system events, examine historical records, and execute emergency response measures (Figure 3).

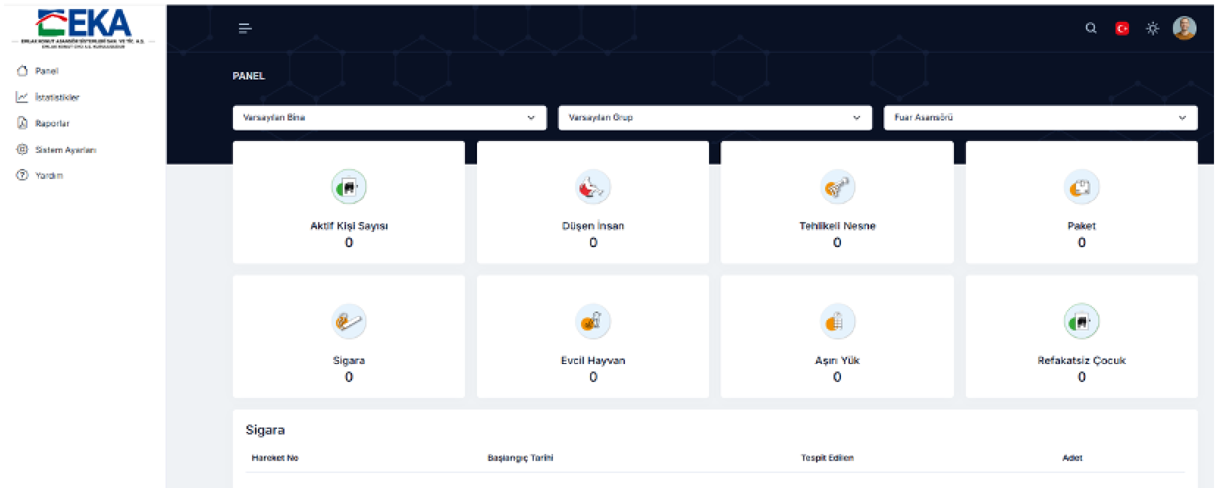

Figure 3 Web-based user interface

Additionally, a mobile application is included as a software component, allowing authorised personnel to monitor incidents and execute remote countermeasures if required. The images obtained from the wide-angle camera are processed using the YOLOv8 [14] object detection algorithm, together with the OpenCV [15] and NumPy libraries [16] for image processing. Face-blurring algorithms are applied for privacy protection, while psycopg2 [17] and PostgreSQL [18] are used for database interaction. InsightFace is employed for authentication and face recognition. The authentication/face recognition software identifies individuals and evaluates whether two separate faces belong to the same person. The integrated AI algorithms can be updated over time to improve predictive accuracy in new environments. As a result, system robustness and precision are progressively enhanced over time. Figure 4 depicts the procedural flowchart governing the developed computer vision algorithm. The reliability of the proposed algorithm is evaluated through experimental trials.

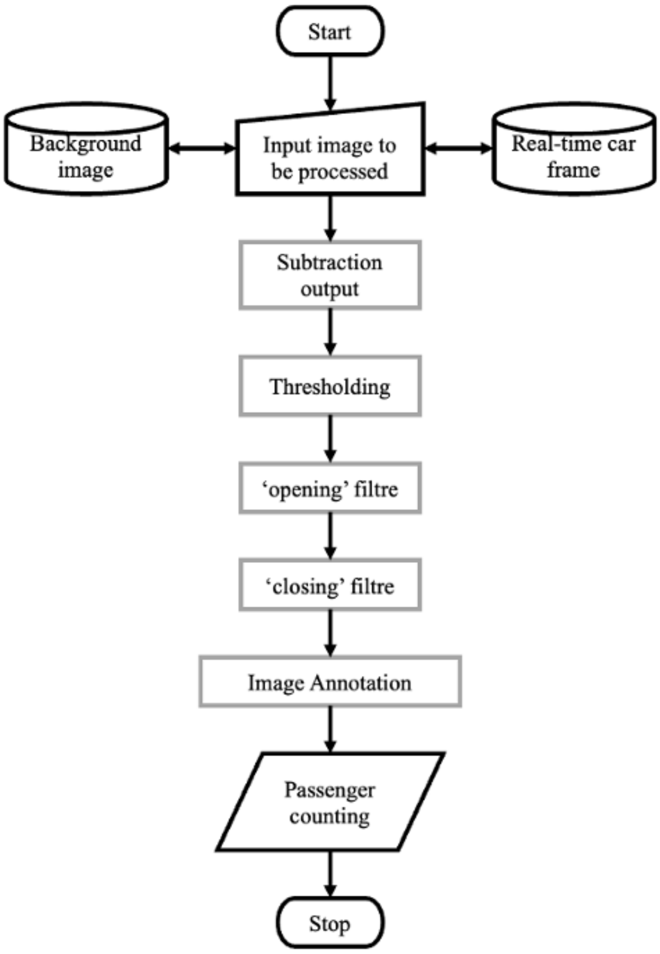

Figure 4 Flowchart of the proposed image processing algorithm

Using both camera-based monitoring and the load weighting system gives the best result because it provides the current number of passengers in the car. In the proposed framework, the visual data representing three occupants within the lift car are captured by the camera and processed in accordance with the steps outlined in the procedural workflow. Additionally, system validation is performed by cross-referencing the computer vision outputs against the weight signals extracted from the load cells under the car floor. Utilising 0.5-second sampling intervals enables the system to infer passenger boarding and alighting activities based on weight fluctuations between these steps. In practice, it is unlikely for multiple individuals to enter the cabin within a 0.5-second window in a single-door lift. The defined threshold values were compared with the difference between steps, and the number of passengers in the elevator car was accurately determined for each step. Figure 5 shows the data obtained from a test run simulating four passengers of different weights getting on and off the example system over a period of two minutes. It shows the weight-step graph processed through a moving average filter where each step represents a 0.5-second weighted average generated using the software developed for the 4-person car configuration selected for the test suite. This cross-validation strategy provides an additional reference for assessing the consistency of the image-based counting results. By comparing visual detections with load-cell variations, possible mismatches caused by occlusion, lighting conditions, or temporary detection errors can be identified.

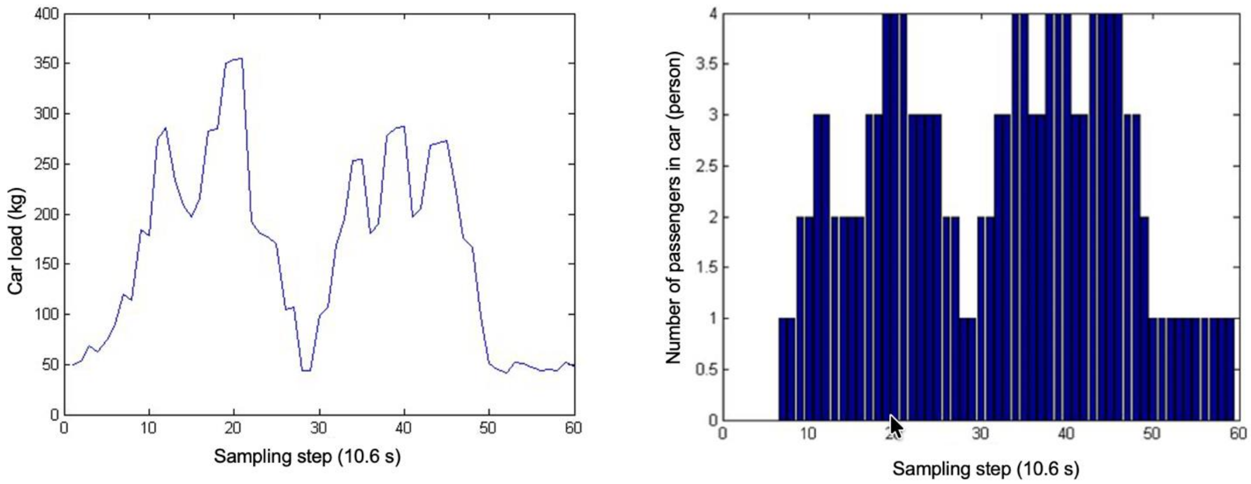

Figure 5 Plot of passenger weight and car capacity count over 0.5 s sampling step

The ESPROS/VOL infrared camera is configured for monochrome imaging to detect the occupancy rate by cross-referencing captured frames against the baseline reference (empty) image. Based on the pixel-intensity variation compared to the empty image, the embedded internal processor transmits the extracted data to the computer over an RS232 serial interface; this transmitted metric specifies the occupancy rate. Furthermore, the proprietary software module generates the occupancy rate as a percentage (%) and estimates the passenger count using this ratio. By means of its proprietary software, the system outputs the occupancy rate as a percentage, which is then utilised to approximate the passenger count. A test suite incorporating a four-person car was employed to evaluate car capacity determination through weight measurement and camera image processing. For this purpose, signals and data from four load cells installed on the car floor were transferred to the computer via the USB-based data acquisition card (MiniLAB 1008) after filtering and amplification processes using an operational amplifier, and numerical values were obtained through the developed software.

Additionally, the image captured by the car-mounted camera was transferred to a computer and calibrated using the CEDES ESPROS software package; the resulting occupancy rate screens provided by the software for one, two, and three passengers are shown in Figure 6.

20 % occupancy rate for 1 person | 31% occupancy rate for 2 persons | 42 % occupancy rate for 3 persons

Figure 6 Occupancy rate for different number of passengers

The weight data, sampled at 200 Hz via a data acquisition card, were passed through an average filter and downsampled to 0.5-second intervals, thereby eliminating undesired artifacts such as noise and oscillations. The camera is fixed at an elevated location to maintain a minimum distance of 2.5 meters from the ground. As an example, the extraction of the passenger metric for three individuals through image processing techniques is presented in Figure 7.

Figure 7 Object detection output for a car with three passengers

The proposed model was trained using a 10,000-image dataset. Initially, 300 custom lift-environment images were uploaded to Roboflow [19], a computer vision platform that provides tools for image annotation, dataset management, preprocessing, augmentation, and dataset export for model training. Using this platform, rotation, noise addition, scaling, and mirroring were applied to expand the dataset to 10,000 samples. The repository was subsequently divided into 75% training, 12.5% testing, and 12.5% validation subsets [20]. The proposed architecture operates on an event-driven basis rather than continuous surveillance, restricting video acquisition solely to critical, restricted, or risk-bearing incidents. Pursuant to data privacy standards, a face-blurring mechanism is applied to support the anonymisation of individuals within the logged footage. Initial model optimisation was executed via an NVIDIA P4000 GPU for 100 cycles; however, the preliminary outcomes proved suboptimal. This performance shortfall necessitated the exploration of alternative repositories hosted on Roboflow, leading to the integration of roughly 10,000 supplementary samples from diverse sources. Subsequently, a second training phase was conducted for the same number of epochs using the augmented dataset. The YOLOv8s architecture demonstrated optimal outcomes upon completing a 100-epoch execution phase. Consequently, four primary evaluation metrics were used to assess the performance of the YOLOv8s architecture.

The compiled repository integrates open-source video sequences with custom-captured photographs, encompassing a diverse spectrum of human postures and locomotor activities such as ambulation, falling, inclination, sitting, and crouching. The procedural workflow for identifying fall incidents is illustrated in Figure 8.

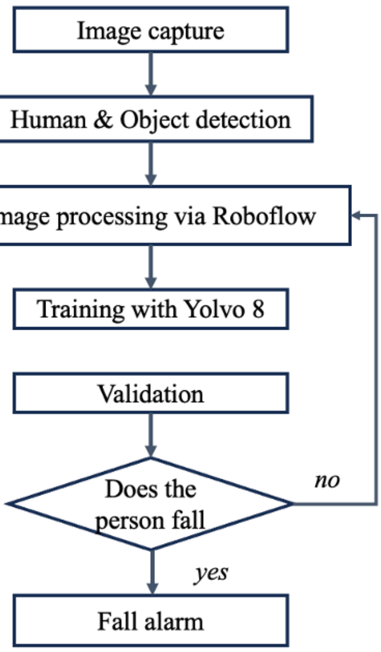

Figure 8 Flowchart of fall detection

These performance indicators confirm that the model is highly effective at recognising human falls. The model demonstrated a continuous decline in both training and validation losses, indicating stable learning. In the event of an anomaly within the developed system's cabin, the lift reroutes to the closest floor and opens its doors at a secure level; meanwhile, the existing emergency communication framework is activated to perform a GSM call.

4 CONCLUSION

Integrated with artificial intelligence-based image processing and object recognition technologies, this smart lift system is developed for high-rise structures – such as commercial and residential buildings operating under heavy traffic – and areas where user safety and comfort are prioritised. By utilising computer vision for lift occupancy estimation, this study addresses the inherent limitations and shortcomings of conventional counting methodologies. Engineered for areas with high-density lift traffic, such as high-rise structures, malls, hotels, hospitals, industrial facilities, and commercial complexes, this smart lift system integrates AI-based computer vision and object recognition technologies, offering a solution with practical applicability.

The practical viability of the proposed system is validated by its fall detection performance (85% precision and 82% recall), indicating that its integration into conventional lift controllers can support faster emergency response. The developed website interface enables the monitoring and tracking of passengers in the car, small children, pets, belongings, and potentially hazardous situations. Future work will focus on integrating the system with building security systems.

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Vertical Transportation in Super-Tall Luxury Residential Towers in India

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Keywords: super-tall residential towers, luxury high-rise housing, smart destination control, human-centric mobility

Abstract. The evolution of luxury high-rise residential towers in India has fundamentally reshaped expectations from Vertical Transportation (VT) design. As developers pursue increasingly premium living experiences, lifts are no longer mere utility components but core lifestyle enablers that define comfort, privacy, security, and service efficiency. Contemporary VT planning integrates intricate user profiling – residents, visitors, house helps, service personnel, and even pets – to ensure seamless movement patterns within dense vertical communities.

Design strategies now emphasise differentiated circulation, with dedicated passenger, service, and fire-rated evacuation lifts that minimise cross-flow and protect resident privacy. Smart destination control systems improve handling capacity during peak periods, while personalising journeys through touchless access, app-based call registration, and zoned access restrictions. The rise of pet-friendly luxury homes introduces additional considerations such as quieter cabins, anti-microbial interiors, and selective pet-movement routing to avoid resident–pet conflicts during peak hours.

Furthermore, the role of house helps – a unique aspect of Indian residential dynamics – requires sensitive VT planning. Separate service cores, back-of-house lift access, and controlled lobby sequencing enable efficient daily operations without compromising the upscale experience expected by homeowners. Visitor traffic is managed through integrated lobby management systems and distributed lift banks that reduce waiting times while maintaining high security standards.

Across Indian cities like Mumbai, Gurgaon, Bengaluru, Hyderabad, and Chennai, VT design now contributes significantly to the overall luxury perception of a tower. The integration of AI-driven traffic prediction, energy-efficient regenerative drives, and high-speed lifts ensures both sustainability and performance. Ultimately, the shaping of VT in India's luxury high-rise segment reflects a shift towards human-centric mobility – one that anticipates every user journey, celebrates convenience, and ensures that vertical living remains effortless, elegant, and future-ready.

1 INTRODUCTION: THE RISE OF SUPER-TALL LUXURY LIVING IN INDIA

India's urban skyline has undergone a dramatic transformation over the last two decades. Once dominated by low-rise and mid-rise housing, metropolitan cities are now witnessing the rapid emergence of *super-tall luxury residential towers*, redefining both urban density and aspirational living. These developments are not merely taller buildings; they are vertical ecosystems that integrate luxury, exclusivity, sustainability, and cutting-edge technology.

At the heart of this vertical evolution lies *Vertical Transportation (VT*) – lifts and escalator systems that no longer serve as simple conveyance mechanisms, but as critical enablers of comfort, privacy, safety, and prestige. In luxury residential towers rising 200–300 metres and beyond, lift systems become the backbone of daily living, influencing resident experience as much as architecture or interior design.

This paper explores how lifts in super-tall luxury residential towers in India have evolved, beginning with a geographic overview of luxury high-rise development, followed by emerging trends, design philosophies, and the future of vertical living.

Figure 1

2 GEOGRAPHY OF SUPER-TALL LUXURY RESIDENTIAL TOWERS IN INDIA

India's super-tall luxury residential tower market is entering a decisive growth phase, driven by rapid urbanisation, land scarcity, and the sharp rise in high-net-worth demand. The segment is increasingly dominated by vertical living solutions where luxury is expressed through height, exclusivity, and integrated amenities rather than horizontal sprawl. Cities like Mumbai continue to lead this transformation, accounting for nearly 60% of the country's tall buildings**,** with multiple 250–300+ metre residential towers redefining urban density economics. Lokhandwala, Minerva and Palais Royale exemplify this shift toward ultra-luxury vertical communities, combining scale with premium positioning.

Geographically, while Mumbai remains the epicentre, the growth curve is clearly widening across India's urban hierarchy. The Delhi NCR – particularly Gurugram – has emerged as a major luxury hotspot, even overtaking Mumbai in high-end sales growth recently, signalling a shift toward north Indian markets. Simultaneously, southern cities like Bengaluru and Hyderabad are embracing vertical luxury, driven by IT-led wealth creation and globalised buyer aspirations. These cities are witnessing a transition from mid-rise premium housing to 40–60+ floor towers, supported by infrastructure expansion and relaxed FSI norms. Importantly, the luxury housing boom is no longer confined to metros but is spreading into emerging urban centres, reflecting a maturing and geographically diversified market.

Going forward, this trend is set to dramatically reshape Indian skylines over the next decade. Super-tall residential towers will increasingly cluster along transit corridors, waterfronts, and CBD peripheries, creating dense "vertical luxury districts" rather than isolated towers. Skylines will evolve from low-rise, fragmented forms to globally comparable high-rise silhouettes, particularly in Mumbai, Gurugram, and Bengaluru. At the same time, rising land values and sustained demand for premium housing – now forming a dominant share of new launches – will push developers toward even taller, more technologically advanced buildings. The result will be a visible shift in India's urban identity: from horizontal expansion to iconic, skyline-defining vertical living that signals both economic growth and aspirational urbanism.

Figure 2

3 GROWTH TRENDS IN LUXURY RESIDENTIAL TOWERS AND VT DEMAND

This vertical expansion is directly translating into intensified demand for advanced VT systems. Luxury towers today are no longer just tall – they are high-density, high-speed environments with expectations of minimal waiting times, privacy, and seamless movement. As buildings grow taller and more complex, VT design is shifting toward destination control systems, high-speed lifts, sky lobbies, and zoning strategies to manage traffic efficiently. Ultra-luxury formats such as sky villas and branded residences further drive demand for low-density lift planning (fewer apartments per lift), private lifts, and service segregation, increasing the number of lifts per tower. Additionally, the integration of smart technologies and sustainability goals is pushing adoption of energy-efficient systems, regenerative drives, and AI-based traffic management.

Looking ahead, as India continues its transition toward super-tall residential clusters and mixed-use vertical developments, VT will become a critical differentiator rather than just an infrastructure component. With luxury housing prices rising sharply (in some cases up to 30–40% YoY in key cities) and demand expected to remain strong, developers will increasingly invest in premium VT solutions to match buyer expectations for comfort, speed, and exclusivity. This positions the VT industry as a central enabler of India's evolving skyline – where engineering performance, user experience, and sustainability converge to support the next generation of luxury living.

4 EVOLUTION OF LUXURY HIGH-RISE RESIDENTIAL VT DESIGN IN INDIA

The evolution of vertical transportation (VT) design in super-tall luxury residential buildings reflects a clear shift from purely functional systems to highly integrated, experience-driven infrastructure. In earlier high-rise residential towers, lifts were treated as isolated service components, primarily focused on basic movement and acceptable waiting times. However, with the rise of super-tall living, VT strategy is now embedded at the concept stage of building design, influencing core layouts, floor zoning, and even architectural form. Systems such as shuttle lifts, sky lobbies, and zoned lift banks have become standard to optimise space and efficiency, while innovations like double-decker and twin lifts have significantly increased handling capacity without expanding core size.

A second major evolution is the technological transformation driven by height, speed, and user expectations in luxury living. Super-tall residential towers now routinely deploy high-speed lifts in the range of 6–10 m/s, where engineering challenges shift from simple transportation to managing vibration, pressure changes, and ride comfort. This has led to advancements such as carbon-fibre hoisting belts enabling greater travel heights, AI-enabled destination control systems that optimise passenger flow, and predictive diagnostics that enhance safety and reliability. Energy regeneration, smart dispatching, and digital monitoring have also become integral, reflecting a move toward intelligent, self-optimising VT ecosystems rather than mechanical systems.

Finally, in luxury residential towers, VT design has evolved into an extension of architecture and lifestyle branding. Lifts are no longer hidden cores but curated spatial experiences – featuring panoramic glass cabins, bespoke material finishes, and seamless integration with interior design language. This aligns with a broader trend where lifts contribute to the identity of premium developments, enhancing views, light, and exclusivity. Additionally, post-pandemic preferences have accelerated touchless controls and personalised access systems, reinforcing privacy and wellness. Together, these shifts highlight how VT in super-tall luxury residences has transitioned from "movement infrastructure" to a critical differentiator shaping both building performance and resident experience.

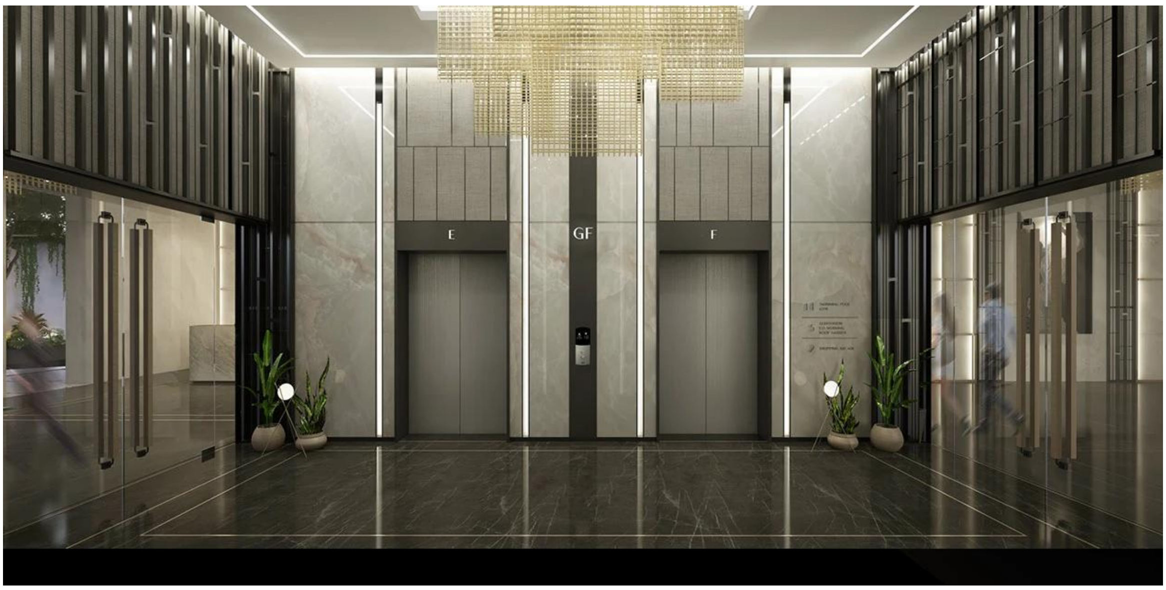

Figure 3

5 DIFFERENTIATED CIRCULATION STRATEGIES IN LUXURY TOWERS

In super-tall luxury residential buildings in India, VT circulation is no longer a simple "lift count" exercise but a highly optimised strategy balancing space efficiency, travel time, privacy, and user experience. Since lifts can consume a significant portion of the core, circulation planning directly influences sellable area and building economics. Unlike commercial towers, residential traffic is more dispersed and less peak-driven, allowing slightly higher acceptable waiting times (typically 45–90 seconds), but luxury developments demand superior comfort, minimal crowding, and near-seamless movement.

A fundamental strategy is zoning and segmentation of the building into vertical neighbourhoods. This is typically achieved through low-, mid-, and high-rise lift banks or through sky lobby concepts, where residents transfer from high-speed shuttle lifts to local lifts serving smaller floor clusters. This approach reduces the number of stops per lift and improves handling capacity without excessively increasing shaft count. In very tall towers, this effectively creates "stacked buildings," each with its own local circulation system fed by express lifts, optimising both efficiency and core size. In Indian luxury projects – especially in Mumbai and emerging Bengaluru high-rises – this also enables exclusivity by limiting the number of apartments served per lift bank.

Advanced circulation options increasingly include double-deck lifts, destination control systems, and hybrid shuttle-local configurations. Double-deck lifts can halve the number of shafts by serving alternate floors, while destination dispatch groups passengers intelligently to reduce stops and waiting times. High-end residential towers may also incorporate private lifts, zoned service lifts, and separate circulation for staff and goods, addressing privacy and operational efficiency. Emerging technologies such as twin lifts in a single shaft and AI-based traffic control further enhance performance, making VT design a key differentiator in India's super luxury residential segment.

Figure 4

6 SMART DESTINATION CONTROL AND PERSONALISED VERTICAL JOURNEYS

The incorporation of smart and AI-driven technologies is rapidly redefining VT circulation in super-tall luxury residential buildings across India. Advanced destination control systems, powered by machine learning algorithms, are now capable of predicting traffic patterns based on time of day, resident behaviour, and even seasonal occupancy trends. These systems optimise lift grouping, reduce wait times, and enhance handling capacity – critical in towers exceeding 50–70 storeys. Integration with IoT-enabled building management systems further allows real-time monitoring of lift performance, energy consumption, and predictive maintenance, ensuring both operational efficiency and minimal downtime – key expectations in the luxury segment.

AI is also enabling a shift from generic to highly personalised VT journeys. Through mobile apps, facial recognition, or access control integration, lifts can identify residents even before they reach the lobby. The system can automatically assign lifts, pre-select destination floors, and adjust cabin settings such as lighting, ventilation, or even preferred music. In ultra-luxury developments, private or semi-private lift zoning is enhanced with AI to learn user preferences over time, ensuring a seamless and discreet travel experience. This level of personalisation not only improves convenience but also reinforces exclusivity – an increasingly important differentiator in India's premium residential market.

Looking ahead, the convergence of AI with data analytics and digital twins will further elevate VT planning and operations. Developers and consultants can simulate resident movement patterns during the design stage itself, allowing for highly optimised core layouts and elevator configurations. Post-occupancy, continuous learning systems will refine traffic strategies dynamically, adapting to evolving usage patterns. In essence, VT in super-tall luxury buildings is transitioning from a functional necessity to an experiential, intelligent service – one that quietly anticipates resident needs and delivers a frictionless, almost hotel-like mobility experience within private homes.

Figure 5

7 PET-FRIENDLY LUXURY HOMES: NEW VT DESIGN CONSIDERATIONS

Pet-friendly VT design in super-tall luxury residential buildings in India is emerging as a niche but important layer of user-centric planning, reflecting the growing recognition of pets as integral family members. From a regulatory standpoint, bodies like the Animal Welfare Board of India have clarified that pets cannot be denied access to common facilities such as lifts, reinforcing the need for inclusive design rather than restrictive policies. In high-rise luxury contexts, this translates into designing VT systems that balance comfort, hygiene, and social sensitivities among residents. Pet-friendly planning begins with zoning – locating lift lobbies away from high-activity pet areas, providing clear circulation paths, and ensuring calm, uncluttered waiting zones so that pets are not overstimulated at entry/exit points.

A key technical and experiential aspect is the design of the lift itself. Enclosed cabins, smooth acceleration/deceleration, low-noise operation, and advanced door safety sensors are critical to ensure pets are not startled or injured. Features such as infrared or pressure-sensitive door edges, longer door dwell times, and visual clarity inside the cabin help create predictable and safe behaviour patterns for animals. Since most incidents occur at entry/exit rather than during travel, design attention must focus on threshold detailing, visibility, and controlled door operation. In luxury towers, this is increasingly integrated with smart destination control systems – allowing residents with pets to select less crowded cars or specific lift groups, enhancing both privacy and comfort.

In super-tall residential developments, the concept of *dedicated or segregated pet-friendly lifts* is gaining traction, though it must be handled sensitively to avoid perceived discrimination. Instead of exclusion, best practice is to integrate pet usage within service or secondary lift banks – similar to logistics or staff movement strategies – while maintaining equivalent quality standards. This aligns with global residential trends where service lifts double up as pet-access lifts during peak hours or designated time slots. The advantage is twofold: it reduces congestion and hygiene concerns in primary passenger lifts while ensuring pets have safe, reliable vertical mobility. From a VT planning perspective, this requires careful handling capacity calculations, zoning (low-rise/high-rise stacks), and interface planning at ground and podium levels – especially in Indian luxury towers where pet amenities like grooming zones and walking decks are increasingly part of the podium ecosystem.

Figure 6

8 HOUSE HELPS AND SERVICE DYNAMICS: AN INDIAN CONTEXT

In super-tall luxury residential towers in India, service lift design has evolved from a back-of-house utility to a critical circulation system, driven by the sharp rise in e-commerce deliveries, high dependence on domestic staff, and luxury lifestyle expectations. The National Building Code of India 2016 emphasises that lift planning must account not just for residents but also for service staff population and goods movement, which in high-end residences can be significant due to live-in maids, cooks, drivers, and floating housekeeping staff. This results in a parallel vertical ecosystem – separate from resident passenger lifts – handling continuous two-way traffic of deliveries, waste movement, and staff access, especially in towers exceeding 40–60 floors where inefficiencies quickly translate into long wait times and operational chaos.

From a design standpoint, service lifts in luxury towers are typically high-capacity freight-passenger hybrids, with capacities ranging from 1600 kg to 3000 kg or more, enabling movement of bulk deliveries, furniture, and multiple staff simultaneously. Cabin dimensions are larger, door widths wider, and finishes more robust (scratch-resistant panels, heavy-duty flooring), while speeds are calibrated slightly lower than premium passenger lifts but still optimised for high-rise travel. Integration with service corridors, back-of-house lobbies, and podium-level logistics zones is critical, ensuring that delivery personnel and staff movement remain invisible to primary resident areas. Increasingly, towers are also incorporating smart access control and destination systems that segregate visitor/service traffic digitally, reducing unnecessary stops and improving turnaround efficiency – aligned with broader high-rise lift planning principles of traffic-based design and zoning.

In terms of number, super-tall luxury residential towers in India typically provide 1 to 2 dedicated service lifts per core, scaling up to 3 in ultra-premium developments depending on unit count, staff density, and podium programming. While standard residential cores may have 2–4 passenger lifts, service lifts are sized not just by residents but by “effective population”, including service staff and delivery load, which can significantly increase peak demand. In projects with sky lobbies or zoned vertical systems, service lifts may either run full height or operate within zones with transfer floors. Best practice – especially in Mumbai, Bengaluru, and Gurgaon luxury markets – is to treat service lifts as mission-critical infrastructure, ensuring redundancy (at least two lifts for reliability), time-based usage strategies (peak delivery hours), and seamless integration with waste management and housekeeping operations. This approach acknowledges that in modern Indian luxury living, the efficiency of service movement is as important as the experience of resident mobility.

Figure 7

9 VISITOR TRAFFIC MANAGEMENT IN SUPER-TALL TOWERS

Visitor and guest vertical traffic in super-tall luxury residential towers in India requires a fundamentally different planning philosophy compared to resident traffic, driven by unpredictability, security layering, and experience expectations. Unlike residents – whose movement patterns are relatively predictable – visitor traffic is stochastic and event-driven (guests, parties, service visits), making it critical to incorporate this variability into early-stage traffic analysis and core planning. Typically, luxury towers adopt a segregated circulation strategy, where visitor lifts are either dedicated or semi-dedicated and zoned separately from resident lifts. This ensures privacy for residents while maintaining operational efficiency. In ultra-luxury developments, visitors are often routed via reception-controlled lift banks with destination dispatch systems, where access is granted only after digital or concierge verification, reducing unnecessary stops and improving handling capacity.

A key design strategy is the integration of arrival experience and security with VT systems. Visitors typically enter through grand lobbies with concierge desks, where lift allocation is controlled via smart systems (QR codes, RFID, or app-based invitations). Modern high-rise lift systems increasingly support such intelligent control and group allocation, optimising lift movement and reducing wait times during peak guest inflow. In Indian super-tall luxury towers, this is often combined with sky lobbies or transfer floors, especially in towers exceeding 60–70 storeys, where visitors switch from low-rise shuttle lifts to high-rise local lifts. This zoning significantly reduces core congestion and improves travel time efficiency, particularly during events or high visitor volumes.

From a planning standpoint, the number and capacity of visitor/guest lifts must be carefully calibrated based on peak guest scenarios rather than average daily traffic, such as social gatherings, festivals, or weekends. High-rise lifts in such buildings typically operate at higher speeds (3 m/s and above) and larger capacities to handle these surges efficiently. Additionally, dual-use strategies are often adopted – where certain lifts function as resident lifts during normal periods but switch to visitor mode during peak demand – enabled by intelligent dispatch systems. Ultimately, successful visitor traffic management in luxury super-tall residences in India is a balance between privacy, security, and a seamless hospitality-like experience, ensuring that guest movement is efficient without compromising the exclusivity of resident circulation.

10 EMERGENCY EVACUATION

Emergency evacuation lifts are becoming a critical component of VT strategy in super-tall luxury residential towers in India, driven by both regulatory evolution and practical limitations of stair-only evacuation. Traditionally, lifts were excluded from evacuation during fires; however, modern codes such as the National Building Code of India now recognise that in very tall buildings – especially above 70 m – safe evacuation cannot rely solely on staircases. Accordingly, fire evacuation lifts (or fireman evacuation lifts) are increasingly mandated in high-rise developments through state regulations like UDCPR and DCPR, with some states making them compulsory for towers above 70 m. In super-tall luxury residential towers, these lifts are no longer viewed as optional add-ons but as integral life-safety infrastructure that complements refuge floors, pressurised staircases, and phased evacuation strategies.

From a design standpoint, evacuation lifts in such towers are highly specialised systems engineered for operation under fire conditions. They are typically located within fire-rated, pressurised shafts (often 2-hour fire resistance) with protected lobbies and smoke-stop doors to ensure tenable conditions during use. Unlike regular passenger lifts, they include dual-control systems – allowing fire services to override operations – dedicated emergency power backup, water protection, and enhanced communication interfaces. In luxury residential towers, these lifts are also designed to handle diverse occupant needs, including elderly residents, children, pets, and persons with disabilities, for whom stair evacuation is impractical. Integration with building management systems, fire alarms, and AI-driven evacuation logic is increasingly common, enabling controlled, phased evacuation (for example, evacuating affected and adjacent floors first) rather than full building discharge.

Operationally, emergency evacuation lifts play a dual role: facilitating rapid access for firefighting teams and enabling assisted evacuation of vulnerable occupants. In super-tall Indian residential towers – often exceeding 50–70 storeys – the vertical travel distance makes exclusive stair evacuation time-consuming and physically demanding, especially under panic conditions. Research and global best practices indicate that lift-assisted evacuation significantly improves evacuation efficiency and safety in such contexts. However, their effectiveness depends on rigorous maintenance, periodic testing, and clearly defined standard operating procedures (SOPs), including coordination with local fire authorities. In premium developments, this is further enhanced through resident awareness programs and evacuation drills, ensuring that evacuation lifts are not just a compliance feature but a functional, reliable component of the building's life-safety ecosystem.

11 CONCLUSION: THE FUTURE OF VERTICAL LIVING IN INDIA

The planning of vertical transportation systems in super-tall luxury residential towers in India has evolved into a highly sophisticated exercise that extends far beyond conventional lift design. It now demands an integrated approach that balances traffic efficiency, resident exclusivity, service logistics, technological intelligence, sustainability, pet-friendly mobility, visitor management, and life-safety requirements. From personalised destination control systems and AI-enabled traffic optimisation to dedicated service and evacuation lifts, every aspect of circulation planning must be carefully tailored to the unique operational profile of luxury residential developments. As these towers continue to rise in height and complexity, vertical mobility is increasingly becoming a defining factor in delivering seamless living experiences and preserving the premium positioning of such assets.

Looking ahead, the future of luxury residential VT design in India will be shaped by smarter, greener, and more resilient mobility ecosystems. The successful towers of tomorrow will be those that integrate predictive technologies, energy-efficient systems, adaptive circulation strategies, and robust emergency preparedness into a unified framework. Equally important will be the ability to anticipate evolving resident expectations around privacy, convenience, wellness, and safety. In this context, vertical transportation is no longer merely an engineering utility but a strategic enabler of luxury, operational excellence, and long-term building value in India's next generation of super-tall residential landmarks.

BIOGRAPHICAL DETAILS

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- Chairman, VT committee for IGBC -Systems commissioning module preparation
- Co-Chairman, ECSBC 2025 CODE REVISIONS - Vertical transportation subcommittee for preparing energy conservation sustainability building codes for BEE, Govt of India.
- NBC 2025 standards review panel member
- Member of Syllabus preparation for Lift technician course for Ministry of Labour & Employment, Govt. of India, under Skill Development Initiative.
- Was a member of IGBC (Indian Green Building Council) and Committee, Bangalore.
- Member, FOCUS (Forum of Critical Utility Services)
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Maximum Lift Car Loading Accepted by Passengers in High-Rise Office Buildings: Does Data Support the 80% Rule?

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Keywords: lift passenger behaviour, car capacity factor, automated passenger counting

Abstract. When conducting lift traffic analysis, one of the key modelling choices is passenger capacity: the limit on the number of passengers in a lift car. A widely used convention in the lift industry is the 80% rule, according to which lifts are assumed to be loaded to no more than 80% of their rated capacity. However, the interpretation of this rule varies across practitioners and methods. Lift car loading is likely influenced by multiple factors, such as cultural norms, traffic conditions, rated capacity, and the building segment. Although the 80% rule is a recurring topic in professional discussions, published measurement data remain scarce.

For this study, automatic passenger count data from 34 office buildings were analysed. Some buildings included multiple lift groups, resulting in a total of 52 lift groups. The measurements were conducted in Europe, Asia, the Middle East, Oceania and North America. The results indicate substantial variation in the upper bounds of lift car loading across regions.

1 INTRODUCTION

Lift safety standards define the maximum available car area for a lift with a particular rated load [1,2]. To board a lift, passengers require sufficient free space to satisfy their physical needs as well as cultural or personal preferences. If the serving lift already carries several passengers, waiting passengers need to decide whether to board the lift or wait for the next one. Lift traffic experts' assumptions regarding the maximum number of passengers accommodated by a lift, i.e., *passenger capacity*, have a significant influence on the validity of lift handling capacity calculations and simulations, affecting the functionality and the value of the building.

It was observed already in the 1960s that passengers do not usually fill lifts to their rated capacities [3]. Dr. Barney, the well-known pioneer of lift traffic planning, suggested using 80% design capacity in lift traffic calculations [4]. Dr. Barney encouraged applying this 80% loading factor to the probable capacity, which is estimated by dividing the lift floor area by the area per person and is usually different from the rated capacity. She considered passenger capacity (P) not as an absolute maximum number of people in a lift car at any given moment but as an average. More recent research [5, 6] supports the use of an 80% capacity factor in lift traffic analysis but also points out that it is not the absolute maximum.

Different practitioners justify the 80% limit in several ways. It can be justified on an area basis; typically, no more passengers can fit in the lift due to the limitations imposed by safety standards. It can also be justified by assuming a Poisson passenger arrival process and applying rules of thumb derived from queuing theory. Some lift traffic experts apply both approaches, leading to approximately a 64% car loading limit compared to the rated capacity, depending on lift car size. The larger the rated capacity, the less space is available per person when comparing rated capacity with the lift car area permitted by safety standards. 80% car capacity factor can also be seen either as a pre-set parameter in calculations and simulations, or as an outcome of simulations [e.g. 6, 7, 8].

Different definitions, or interpretations of definitions, of passenger capacity may cause additional confusion. ISO 8100-32:2020 (Chapter 6.5.3) [9] provides two different definitions for passenger capacity depending on whether the analysis is based on a calculation method or a simulation method. The standard defines P_{calc} as the *average* number of passengers in the car at the departure from the main entrance floor, and P_{sim} as the *maximum* number of passengers in the car during simulations. These definitions are not problematic if they are used consistently in the formulae giving the relationship between the rated capacity and passenger capacity. The interpretation problem comes from a note that is on the same page as the definitions in the standard. The note states: "In simulation, the car can load to more than the average, represented by P_{sim}." This raises the question: is P_{sim} the average or maximum? This distinction is critical when determining the correct multiplier (F) in an equation describing the relation of rated capacity (Q) and passenger capacity P_{sim}:

$$P_{sim} = FQ. \quad (1)$$

If P_{sim} is interpreted as an average that can sometimes be exceeded, a multiplier of max 0.8 should be used. If P_{sim} is interpreted as the maximum that is never exceeded, a maximum multiplier of 1 can be justified. Smaller multipliers can be required depending on building segment and other case-specific considerations. In equation 1, rated capacity Q can be replaced with the area-based maximum number of persons if an area-based approach is preferred.

This paper studies the maximum car capacity factors (CCF_{max}) measured in high-rise *office* buildings. The car capacity factor is defined as the ratio of the number of passengers in a lift car to its rated passenger capacity. In this article, the car capacity factor is not averaged over round trips, but the purpose is to find out the highest values that passengers accept at any time.

$$CCF_{max} = P_{max} \,/\, Q \quad (2)$$

2 FACTORS INFLUENCING MAXIMUM CAR LOADING

Several factors influence the point at which a lift is perceived as too crowded to board. These factors can include, for example, culture, time of day, waiting time, handling capacity, building segment, tenancy, gender distribution, number of floors, social group behaviour, personal accessories, lift group control, lift shape, and lift car size – the area per person varies with different rated loads and even lift cars with the same rated load can have different floor areas [5, 10, 11].

This article concentrates on the office segment, including single-tenant and multi-tenant offices. The dataset also includes one building that could be classified as an educational facility and one that could be classified as a parliament building. These were considered sufficiently similar to offices in terms of passengers' space requirements. Other building segments, such as residential buildings, hotels, hospitals, and shopping centres, were not included and would require further research.

The hypothesis is that people in Western countries tolerate lower levels of crowding in lifts compared to, for example, people in South-Eastern Asia. This difference may be partly explained by variations in average passenger size, as well as by cultural norms regarding personal space and acceptable density in shared environments. In addition, familiarity with high-density environments is likely to play a role. Practitioners in the field have also suggested that Northern Europeans may utilise lift capacity less efficiently than Southern Europeans.

Previous pilot research [5] indicated that higher car loadings would be accepted by passengers during lunchtime and evening peak than during morning uppeak. Therefore, this is now analysed using a larger dataset.

3 COLLECTED DATA

Data were collected using stand-alone sensor devices that were temporarily installed in the lifts. Using 3D camera technology and human detection algorithms, the sensors detected boarding and alighting passengers with an accuracy greater than 95%. The passenger counts were used to derive car capacity factors after each stop [5, 12].

Measurements were conducted on several continents: Asia, Oceania, Europe and North America. The European sample included buildings from Northern, Southern, Eastern and Western Europe. The Asian dataset consisted of measurements from the regions of Southeast Asia, East Asia and the Middle East. Most of the buildings had at least minor lift traffic challenges, as most of the data was originally collected to support customers in improving people flow in their buildings, although some buildings with good lift traffic were also included. None of the regions had only well-lifted buildings.

The data were collected between 2017 and 2025, but not during the COVID-19 restrictions or in the period following them, when passenger behaviour may have differed from normal conditions. Some of the buildings included several lift groups located in different zones. The zones may have differed significantly, effectively functioning like separate buildings with different tenants and traffic profiles, as well as different passenger behaviour. Some lift groups had only one day of measurement data, while others had up to 7 days of data. All the measurement days were weekdays. Lift car sizes included in the research varied from 8 to 26 persons rated capacity, according to a 75 kg per person standard.

Table 1 Overview of the measurements by region, including countries, number of buildings, lift groups and measurement days

Region	Countries	Measured buildings	Measured lift groups	Measurement days
Eastern Asia	China	2	3	5
South-Eastern Asia	Indonesia, Singapore, Malaysia, Philippines, Thailand	12	19	31
Middle East	Türkiye, UAE	5	5	6
Eastern/Central Europe	Poland, Serbia	2	2	4
Western Europe	France, Belgium, Netherlands	4	10	15
Northern Europe	Finland, Sweden	3	3	13
Southern Europe	Spain	2	3	6
Oceania	Australia	2	2	5
Northern America	USA, Canada	2	5	8
Total		**34**	**52**	**93**

4 RESULTS

One of the research questions is to determine the highest acceptable car capacity factors at different times of the day and in different regions or cultures. One challenge when analysing the data was that peak periods occurred at different times in each building, and direct averaging over timestamps would have flattened the peaks. On the other hand, maximum values can be affected by outliers or measurement errors.

To address this, the following approach was applied. For each lift and measurement day, the highest-loading 15-minute interval was identified separately for three peak periods: morning, lunch and evening. This ensures that peak conditions are captured regardless of their exact timing in different buildings.

From the observations within these peak intervals, the 99.5th percentile of car capacity factors ($CCF_{99.5}$) was calculated. This provides a robust estimate of the upper bound of passenger-accepted loading while excluding extreme outliers. Results should be interpreted cautiously for regions with limited sample sizes.

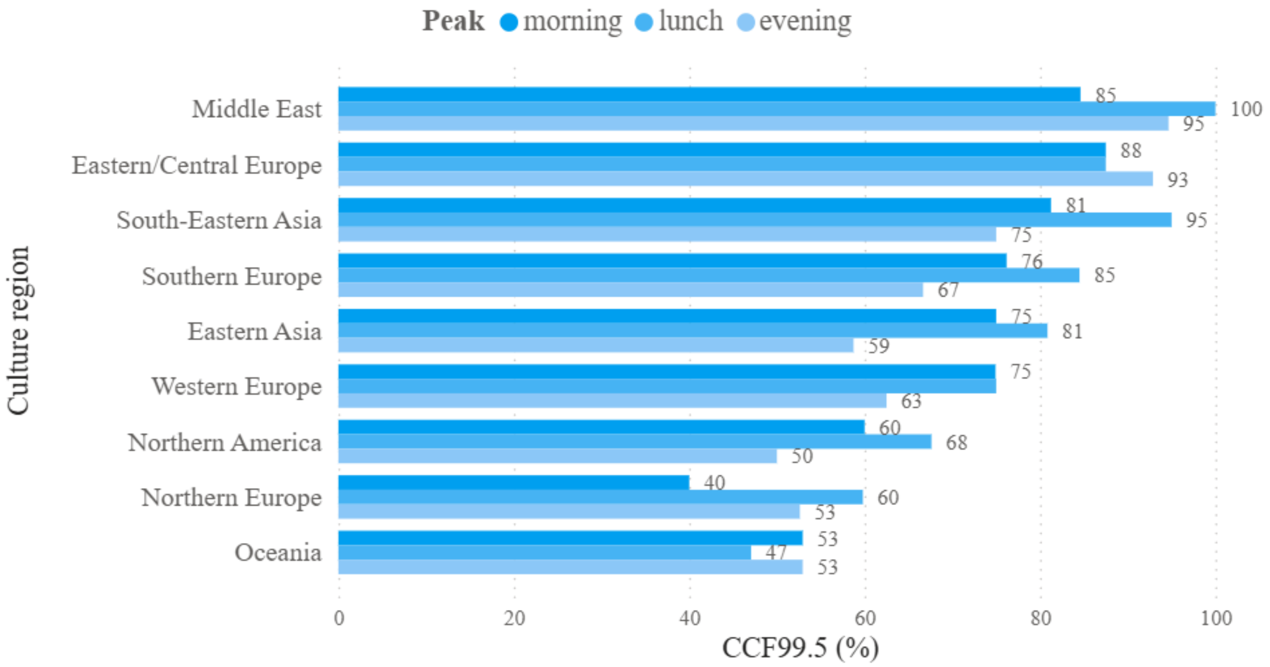

Figure 1 $CCF_{99.5}$ during worst morning, lunch and evening peak periods by cultural region

In addition to the detailed regional classification, a secondary grouping was constructed to improve statistical robustness. The alternative groups are Europe, Asia and Anglo-cultural regions. This complementary classification does not replace the original regional breakdown but provides a more aggregated perspective. However, this classification alone would be too coarse to capture meaningful variation in lift loading behaviour.

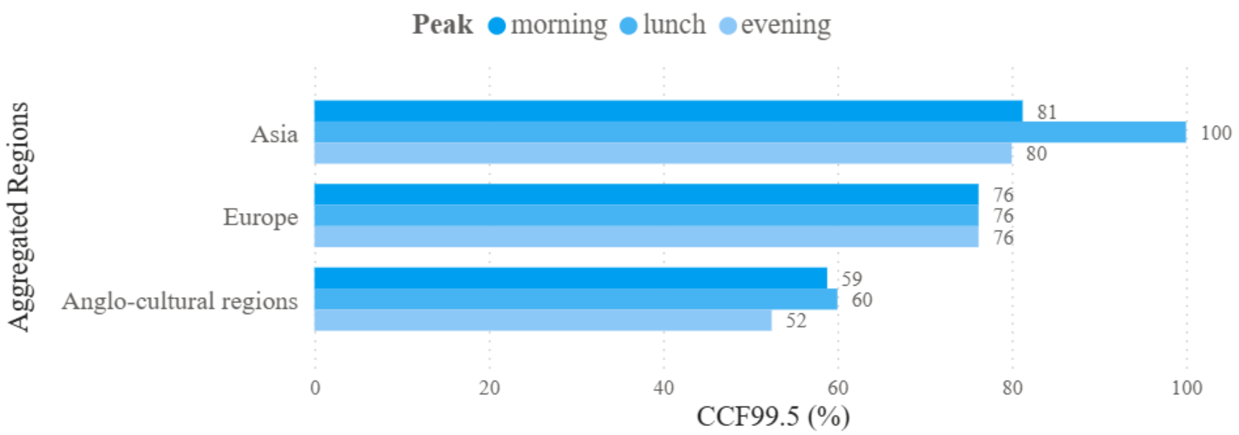

Figure 2 $CCF_{99.5}$ during worst peak periods by aggregated region

In Asia, the upper range of accepted car capacity factors appears to reach approximately 80% during morning and evening peak periods, and up to around 100% during the lunch peak. This reflects the upper tail of the observed load distribution rather than typical operating conditions. The higher values observed during lunch compared to morning and evening peak periods may be associated with increased traffic demand, longer waiting times, or a higher likelihood of passengers travelling in socially connected groups.

Across Europe, accepted car capacity generally remains below 80%. More detailed analysis reveals notable intra-regional variation, with Northern Europe demonstrating significantly lower loading levels. This observation is consistent with the authors' experience, although the sample size in Northern Europe is limited.

The lowest car capacity factors were observed in Anglo-cultural regions. Although the dataset did not include measurements from the United Kingdom, this pattern is consistent with industry practices in these regions. For example, British lift consultants often prefer area-based methods for defining passenger capacity, which typically result in lower car loading compared to mass-based approaches. Both approaches are permitted under ISO 8100-32:2020.

In addition to cultural reasons, regional differences are probably influenced by passenger sizes. CIBSE Guide D [11], which is commonly used in countries with strong British influence, presents passenger sizes varying from 0.14 to 0.24 m^2 per person in different countries. More precisely, CIBSE Guide D calls this the body area index. After the tables of body area indices, CIBSE Guide D presents an example of a body ellipse with an area of 0.21 m^2. This lets the reader understand that body area indices are body *ellipse areas*. It could be better clarified whether it is correct to divide lift floor area by the presented ellipse area. Passengers are not play-dough and cannot fill every corner of the lift efficiently. On the other hand, the example body ellipse seems to have a bit of tolerance, and the original body ellipse measurements have been done based on an adult male sample population. In practice, mistakes would not be big if lift floor area is simply divided by area per person without complicated ellipse packing analyses.

Figure 3 shows the distribution of car capacity factors across all observations, including non-peak periods. The majority of observations are concentrated at low load levels, reflecting typical operating conditions where lifts are only partially occupied. However, the presence of a long tail demonstrates that significantly higher load levels do occur, although relatively infrequently. This contrast highlights the difference between typical and peak usage: average operating conditions are dominated by low loads, whereas high load levels are rare but still operationally relevant.

Figures 4–6 show the corresponding distributions within the identified worst 15-minute peak intervals for morning, lunch and evening periods. Compared to the full dataset, the distributions are shifted towards higher load levels, as expected.

The most extreme car capacity factors over 130 % did not occur during any peak period. Those might be individual sensor measurement mistakes. Alternatively, the passengers involved may have been smaller than average.

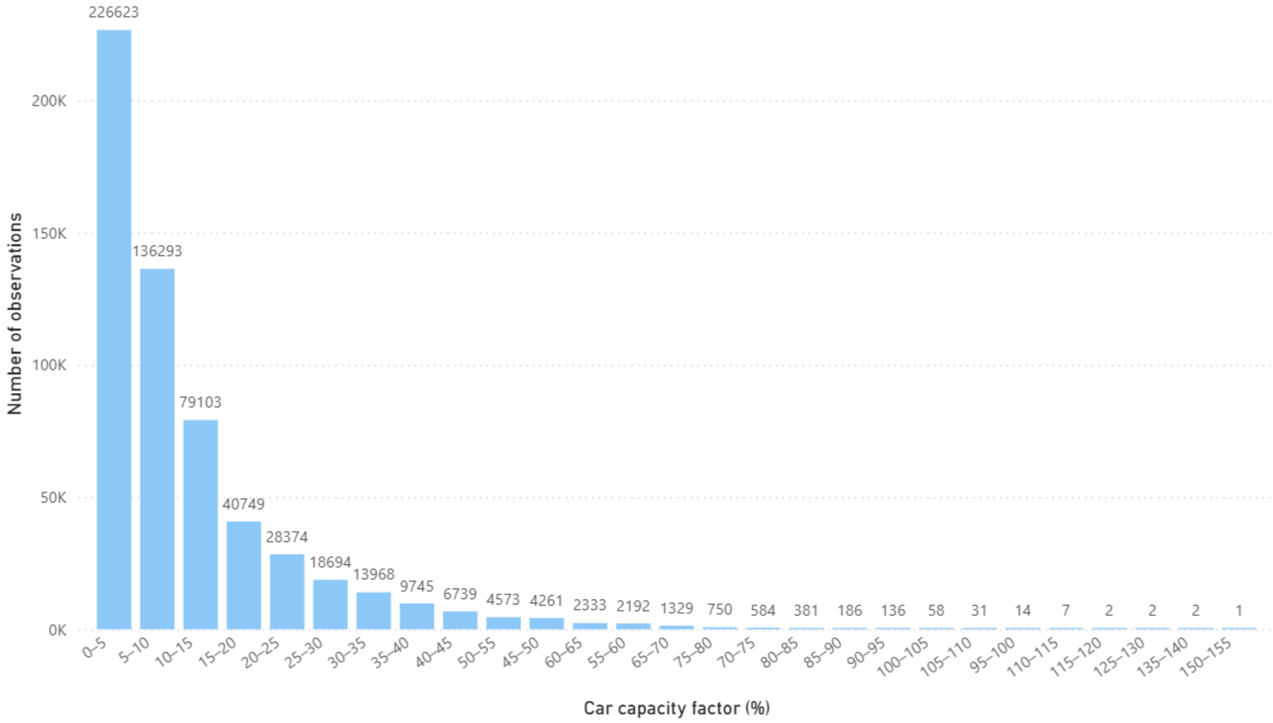

Figure 3 Distribution of car capacity factors including all time periods (also quiet times)

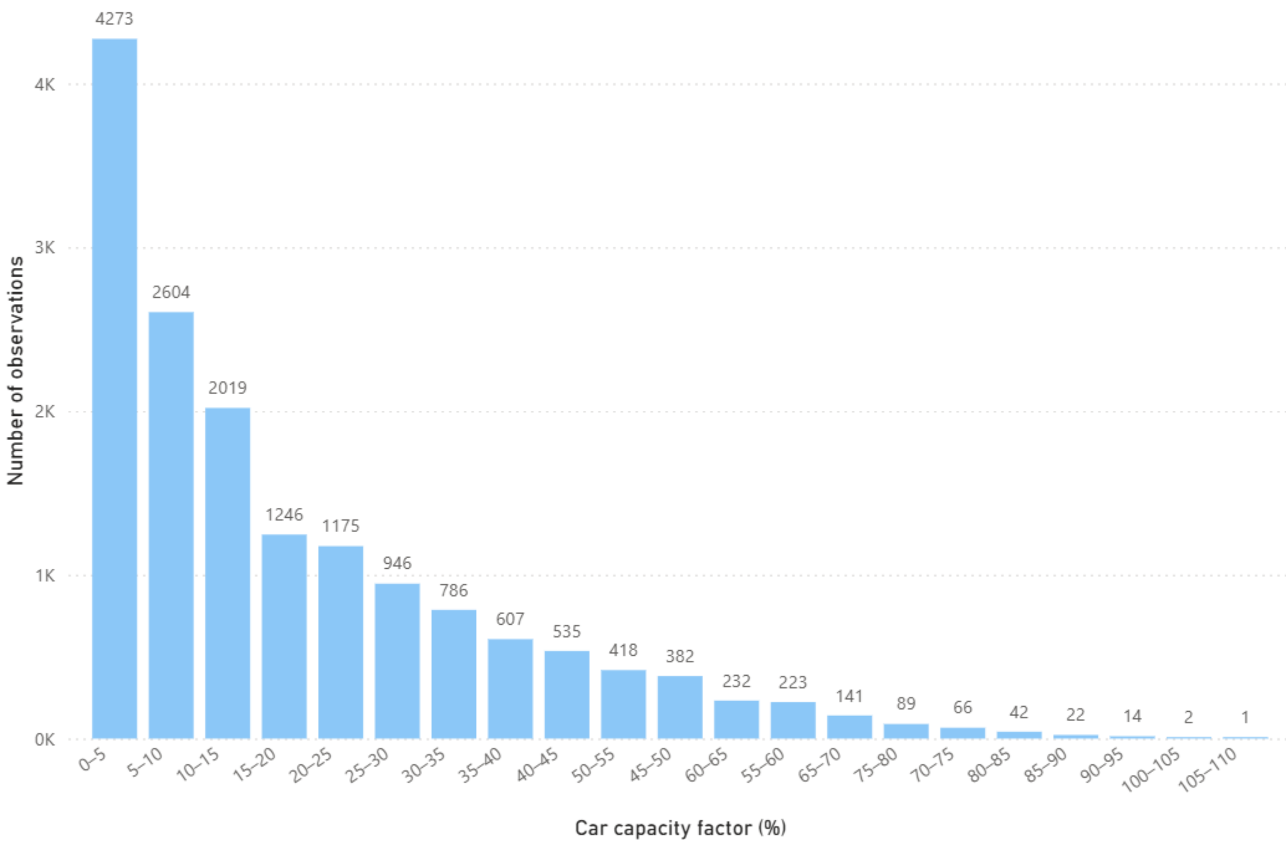

Figure 4 Distribution of car capacity factors during worst 15-minute morning peaks

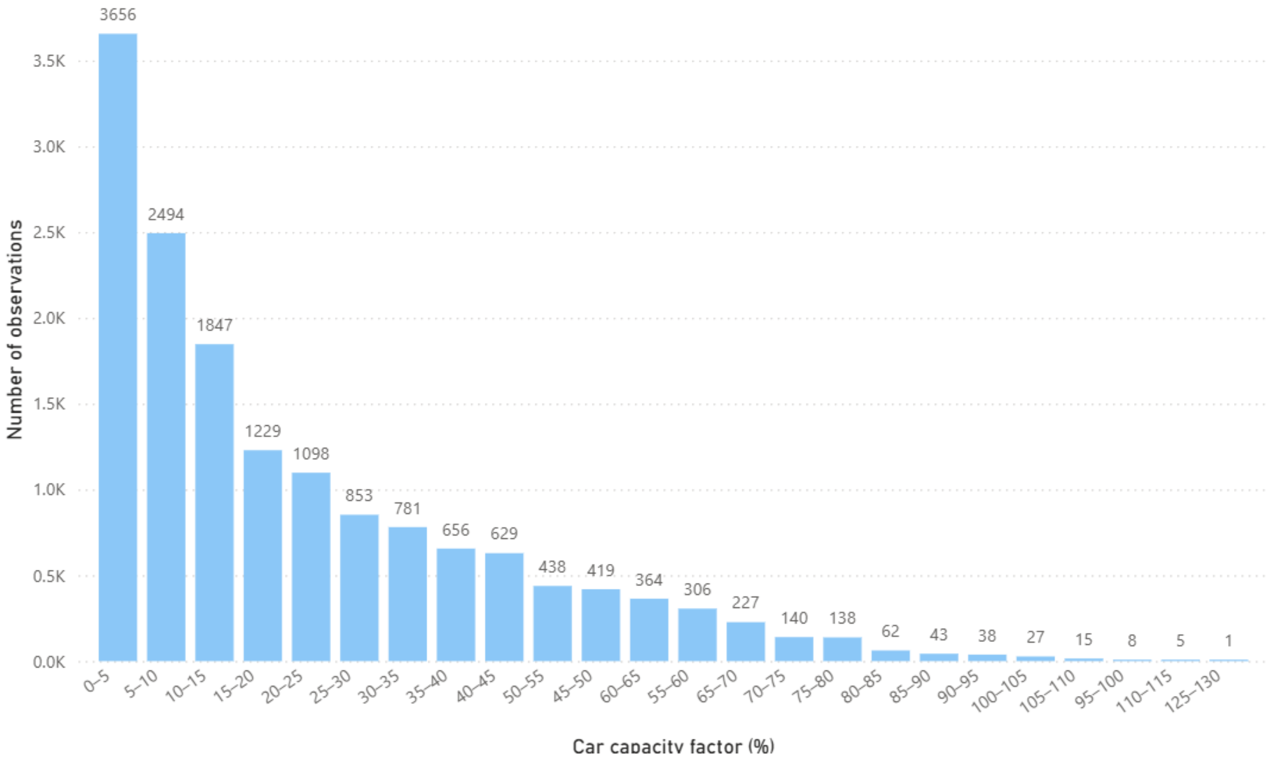

Figure 5 Distribution of car capacity factors during worst 15-minute lunch peaks

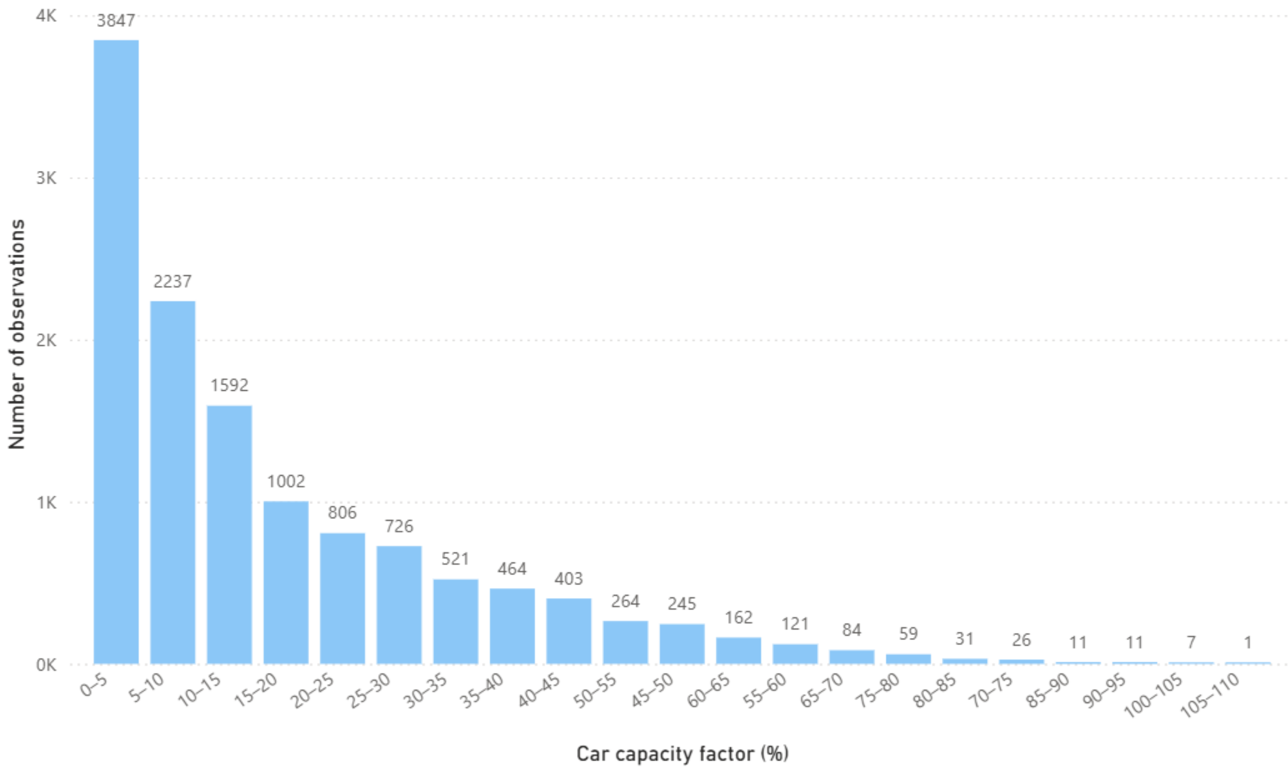

Figure 6 Distribution of car capacity factors during worst 15-minute evening peaks

The negative side of data being collected originally for other purposes is that the authors could not have affected what other data had been collected of the lift groups and buildings in addition to the sensor measurements. The authors have checked, for example, countries and building types, but data such as door parameters or lift floor areas are not available. These could have been beneficial for calculating handling capacity ratios or comparing loading against lift floor areas. Rough approximations could have been possible based on assumptions, but those could have been misleading also.

5 CONCLUSIONS

The results indicate substantial variation in the upper bounds of lift car loading across regions. High-percentile values ($CCF_{99.5}$) suggest that car capacity factors accepted by passengers can approach or reach rated capacity in certain contexts, particularly in Asian regions during lunch peak periods. In contrast, European regions exhibit more moderate car capacity factors, while Anglo-cultural regions show even lower car loading levels. The findings highlight that the upper envelope of car loading is strongly context-dependent.

The results suggest that assumptions regarding acceptable lift car loading should be region-specific rather than universal. The time of day also appears to influence car loading levels. Design approaches based on fixed or globally uniform capacity factors may fail to reflect actual passenger behaviour in different contexts, potentially leading to under- or over-dimensioning of lift systems.

The concept of car capacity factor could be more explicitly defined as an outcome of lift traffic analysis rather than a fixed design assumption. It may be difficult to determine a single global standard loading limit. However, a requirement to present car capacity factor as an analysis outcome could be incorporated into standards and guidelines. Some practitioners already present it in their lift traffic analysis results, and some guidelines [e.g. 11] encourage presenting it. However, other practitioners do not consider car loading levels to be a service criterion alongside waiting time and time to destination. It would be valuable for this requirement to be incorporated into the global lift traffic standard ISO 8100-32.

This does not mean that there would be no physical limits. In practice, lift car area and passenger sizes define the maximum passenger capacity. This maximum value could be used in lift traffic *simulations*. In the *calculation* method, a factor of 0.8 should also be applied. Regional differences are partly taken into consideration if area per person is defined correctly for every region. In addition, lift consultants can specify other context-dependent multipliers. These should be described and explained in lift traffic analysis reports.

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BIOGRAPHICAL DETAILS

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Shifting Gears and Lifting Careers: Women in the Lift Industry

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Keywords: women in engineering, gender diversity, inclusive apprenticeships, workplace culture.

Abstract. Women in the lift and escalator industry represent a small share of the technical, engineering, and leadership workforce. The numbers are growing, but together as an industry we can do more to ensure women enter, stay, and thrive in the sector.

This paper takes a closer look at the experiences behind the numbers, drawing on industry practices and conversations with women working in lift engineering.

Looking at lessons from diversity efforts in related technical fields, the study brings forward themes that many will recognise - limited early exposure to engineering pathways, reports of being discouraged from pursuing mechanical trades during school career guidance sessions, and few visible female role models who show what is possible.

Alongside these challenges, the paper also highlights what is working. Targeted outreach, inclusive apprenticeship routes, supportive mentorship networks, and thoughtful improvements to workplace culture are already making a positive difference.

With practical recommendations for employers, educators, and industry bodies, this research aims to help build a sector where women feel welcomed, supported, and able to progress with confidence. For example, employers can implement mentorship programs pairing new female hires with experienced professionals, while educators can introduce engineering modules tailored to young women.

Encouraging greater female participation is not just about fairness. It strengthens innovation, supports long-term skills growth, and helps the industry meet the evolving needs of the built environment.

A more balanced workforce is not just a goal; it is an opportunity for the industry to grow in a way that benefits everyone.

1 INTRODUCTION

The lift and escalator industry is central to the functioning of places and spaces globally. As buildings grow taller, infrastructure becomes more complex, and end-user and societal expectations in terms of access and egress – including for disabled people – change, the demand for skilled engineers and technicians continues to rise. Despite this demand, which is likely to increase going forward, women remain significantly under-represented across technical, engineering, and leadership roles. This imbalance mirrors wider trends in mechanical and electrical engineering, where women constitute only 16.5% of the UK engineering workforce [1].

Although the number of women entering the lift industry is gradually increasing, statistical and visible change has not been significant. The sector is at a critical juncture: it must expand its talent pipeline, address skills shortages, and adapt to technological change. Encouraging more women to enter, stay, and progress within the industry does not only relate to equity but is also a strategic necessity to ensure the industry can continue to respond to demand going forward. This paper examines the experiences behind the statistics, drawing on industry conversations, comparative research, and emerging best practice. It highlights some of the barriers women experience, initiatives that are working, and opportunities for collective action.

2 EARLY INFLUENCES AND THE FORMATION OF CAREER PATHWAYS

2.1 Gendered expectations in schooling

Women's under-representation in lift engineering often begins long before they enter the workforce. Interviews with female engineers reveal that early exposure to engineering pathways is limited, and gendered assumptions frequently shape career guidance. Many women recall being subtly discouraged from pursuing mechanical trades during school, with teachers or advisers suggesting "more suitable" careers. These experiences reflect broader STEM patterns: girls' interest in engineering peaks between the ages of 11 and 14, but declines sharply when they encounter stereotypes about who belongs in technical fields [2].

Career guidance practices often reinforce these patterns. Engineering UK [3] reports that girls are less likely than boys to receive information about apprenticeships or technical careers and more likely to be directed toward traditionally feminine sectors such as health or education. Without early exposure to engineering tasks or relatable role models, many young women simply never consider lift engineering as a viable option.

2.2 The importance of early hands-on experience

Practical engagement plays a crucial role in shaping career aspirations. Research from the Royal Academy of Engineering [4] highlights that hands-on activities – such as dismantling mechanical systems, coding workshops, or engineering challenges – significantly increase girls' confidence and interest in STEM. In the lift industry, opportunities for early engagement remain limited, but targeted outreach programmes are beginning to address this gap. Companies that offer school visits, interactive demonstrations, or taster days report higher engagement from female students.

3 REPRESENTATION AND VISIBILITY IN THE INDUSTRY

3.1 The impact of role models

Visibility is a powerful driver of inclusion. Women entering the lift industry frequently report being the only female engineer in their team or region, which can heighten feelings of isolation and a lack of belonging, as well as a sense of being othered within the profession. This aligns with findings from the Women's Engineering Society (WES) [5], which emphasises that the absence of visible female role models contributes to lower recruitment and retention. Conversely, when women see others thriving in technical roles, their sense of belonging increases. Industry outreach events that feature female engineers consistently attract higher engagement from girls and young women [6].

Representation also helps challenge persistent stereotypes about physical capability or technical competence. To illustrate these stereotypes, the following anonymised statements have been reported within the industry and wider engineering contexts:

- "This job can be quite physical – are you sure you'll manage the heavier tasks?"
- "Lift fault-finding is very technical; it might be too complex if you haven't done hands-on engineering before."
- "Customers might prefer dealing with a male engineer on site."
- "Women don't usually stay long in this kind of role – it's demanding."
- "You might struggle with some of the tools; they're designed for people with more strength."

Modern lift engineering has evolved significantly with the introduction of advanced diagnostic tools, remote monitoring, and digital systems. These innovations have reduced the physical demands traditionally associated with the role, making outdated assumptions about who can or cannot do the job increasingly irrelevant. Today, the industry recognises that effective lift engineering is driven by technical insight, problem-solving, and collaborative working practices rather than physical strength.

3.2 Challenging stereotypes through visibility

Public-facing campaigns, case studies, and media features should highlight not only women's achievements but also women carrying out everyday roles across the lift industry. Showcasing women in routine technical, operational, and leadership positions helps normalise their presence, challenge outdated stereotypes, and reshape perceptions of who belongs in the sector. This kind of visible, day-to-day representation is particularly influential for younger people forming their first impressions of engineering careers and looking for relatable role models.

4 BARRIERS WITHIN THE WORKPLACE

4.1 Cultural and structural challenges

Women who enter the lift and escalator industry often encounter workplace cultural norms, barriers and/or perceived barriers to inclusion and belonging, which have been shaped and informed (likely unconsciously) by a long-standing male-dominated workforce. Commonly experienced barriers include:

- Being the only woman in a team, leading to feelings of increased scrutiny or focus on one's work due to the novelty of difference.
- Potentially more limited access to traditionally male-dominated informal networks (which women have not been a part of in the past) where opportunities and knowledge circulate.
- Subtle and unconscious biases that can inadvertently steer or encourage women toward administrative or "lighter" tasks rather than complex technical work.
- Workplace banter or behaviours that can unintentionally result in women feeling unwelcome, undermined or undervalued.

These experiences reflect broader patterns in engineering workplaces [7]. While overt discrimination has declined, micro-exclusions and assumptions about gender roles persist. Women may be overlooked for advanced technical training or complex assignments that would build experience, slowing their progression.

4.2 Retention and progression barriers

Retention is a significant challenge. Research from the Institute of Engineering and Technology (IET) [8] shows that women in engineering are more likely than men to leave the profession within the first five years, often citing lack of progression, limited support, or unsupportive culture. In the lift industry, similar themes emerge: women report fewer opportunities for advanced technical training, slower promotion pathways, and limited visibility of women in senior leadership.

5 WHAT IS WORKING: EMERGING GOOD PRACTICE

5.1 Targeted outreach and school engagement

Several lift companies and industry bodies have begun implementing outreach programmes aimed at girls aged 11-16. These initiatives include school visits, engineering workshops, and interactive demonstrations of lift systems. Evidence from STEM Learning UK [9] suggests that such interventions significantly increase girls' interest in engineering careers, particularly when delivered by female engineers.

5.2 Inclusive apprenticeship pathways

Apprenticeships remain a key entry route into the lift industry, and employers who have reviewed and updated their recruitment materials, interview processes, and outreach strategies are reporting increased applications from women. These reviews typically include auditing job descriptions for gendered or overly physical language, replacing stereotypical imagery with photos of women carrying out everyday technical tasks, and providing clearer explanations of modern diagnostic tools and remote-monitoring work to demystify the role. Employers are also refining interview questions to focus on problem-solving and technical curiosity rather than prior hands-on experience, offering flexible working options where possible, and strengthening outreach through school partnerships, taster days, and pre-apprenticeship sessions. Research shows that these practical steps – alongside gender-neutral language and transparent descriptions of day-to-day tasks – can significantly broaden the applicant pool [10].

Some organisations have gone further by introducing pre-apprenticeship programmes designed to build confidence and foundational skills for individuals who may not have had prior technical experience. These programmes mirror successful models used in construction and rail engineering and provide a supported, practical pathway into the industry.

5.3 Mentorship and peer support networks

Mentorship is consistently identified as one of the most effective tools for retention and progression. Pairing new female hires with experienced engineers provides guidance, reassurance, and a safe space to discuss challenges. Industry-wide networks – such as WES, LEIA's Women in Lifts initiative, and cross-sector engineering forums – help women build community and share best practice.

5.4 Improving workplace culture

Cultural change is essential for long-term progress. Employers who invest in inclusive leadership training, clear anti-harassment policies, and transparent progression pathways report higher satisfaction among female staff [11]. Practical, organisation-led improvements also play a significant role in creating a more inclusive and welcoming environment. These include ensuring PPE is available in designs and sizes that accommodate women, reviewing shift patterns to offer greater flexibility, and providing facilities that meet the needs of all employees, including women. By addressing these structural and environmental barriers – rather than placing responsibility on individuals – employers can foster workplaces where women feel supported, valued, and able to thrive.

5.5 Celebrating success and visibility

Showcasing the achievements of women in the lift industry – alongside visible examples of women carrying out and enjoying day-to-day technical and operational roles – helps shift perceptions, normalises women's presence in the sector, and inspires future talent. Case studies, award nominations, and internal communications that highlight both everyday contributions and individual successes reinforce the message that women belong in technical and leadership roles without needing to exceed their male counterparts to be recognised. This balanced approach to visibility supports cultural change and provides relatable role models for those considering a career in the industry.

6 THE STRATEGIC CASE FOR GENDER DIVERSITY

6.1 Innovation and problem-solving

Diverse teams outperform homogeneous teams because they bring a wider range of lived experiences, communication styles, and problem-solving approaches. In the lift industry, women often contribute perspectives shaped by customer interaction, accessibility considerations, and user-centred thinking

– all of which can influence system design, fault diagnosis, and service delivery. Research shows that mixed-gender teams are more likely to challenge assumptions, identify risks earlier, and generate creative solutions [12].

6.2 Addressing skills shortages

With experienced engineers retiring and demand for vertical transportation increasing, the industry cannot rely on traditional recruitment pools alone. Women represent a large, under-utilised talent pipeline. Broadening participation strengthens workforce resilience, supports succession planning, and ensures the industry can meet future demand.

6.3 Aligning with client and public expectations

Clients and regulators increasingly assess organisations on their commitment to diversity and inclusion. A visibly balanced workforce enhances credibility, supports tender processes, and aligns with public expectations around equality. Demonstrating progress in gender representation can therefore strengthen commercial relationships and industry reputation.

7 CONCLUSION: AN OPPORTUNITY FOR COLLECTIVE ACTION

The lift and escalator industry is well positioned to become a sectoral leader in advancing gender inclusion within engineering. Evidence of progress is already emerging through targeted outreach initiatives, more inclusive apprenticeship pathways, strengthened mentorship networks, and the cultural and attitudinal shifts taking place across organisations. Nonetheless, sustained and coordinated action is required to accelerate this trajectory. Employers must continue to refine recruitment and retention practices; educators must ensure that engineering pathways remain accessible and free from gendered barriers; and industry bodies must promote, monitor, and disseminate best practice across the sector.

It is important to recognise that meaningful change will take time. Gendered assumptions and expectations begin forming in early childhood, and shifts in these norms may take a generation to be fully reflected in workforce representation statistics. A more gender-balanced industry therefore represents not only an ethical imperative but a strategic opportunity. By committing to long-term, systemic change, the sector can cultivate an environment in which women enter, remain, and progress with confidence, contributing to a more resilient, innovative, and future-ready workforce.

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BIOGRAPHICAL DETAILS

Gemma Moore is an Account Manager at Dewhurst Ltd, where she manages a portfolio of key clients and supports the delivery of tailored lift solutions across the UK. She holds a BA in International Marketing and a BA in Business Management from Teesside University. With over eight years of experience in technical sales and customer relationship management, she plays a central role in driving new business development and ensuring long-term client satisfaction. Gemma brings a customer-focused approach to the lift industry, with a strong emphasis on service excellence, market insight, and collaborative growth.

Examining the Condition of Hospital Lifts after an Earthquake

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Keywords: earthquake, seismic effect, hospital lifts, damage after earthquake.

Abstract. Among public buildings ordinarily used by the public, health facilities hold a critical priority and importance. During field visits following two major destructive earthquakes in Turkey in the last 15 years, damage to hospital lifts in particular has drawn attention. Hospital lifts, which are of great importance in the treatment of earthquake victims, are desired to be earthquake-resistant after an earthquake. In this study, the damages detected in hospital lifts following the 2011 Van earthquake and the 2023 Kahramanmaraş twin earthquakes in Turkey are evaluated, and the techniques developed and implemented for earthquake-resistant lifts are explained with examples.

1 INTRODUCTION

Hospitals have an important role among public buildings after destructive earthquakes. They are expected to continue healthcare services and to respond to emergency medical demand during the post-earthquake period. Therefore, the seismic performance of hospitals should not be evaluated only by considering the structural safety of the building. Non-structural components and service systems can also affect the functionality of a hospital. Damage to these systems may cause interruption of hospital services even when the main structural system remains usable [1,2]. Hospital lifts are one of the important service systems for maintaining vertical transportation in healthcare buildings. They are used for the transportation of patients, stretchers, beds, medical staff, visitors, medical devices, medicine, food, and service equipment. In ordinary buildings, lift failures generally cause accessibility and comfort problems. However, in hospitals, lift failures can directly affect patient transfer, emergency response, and internal logistics. For this reason, the post-earthquake condition of hospital lifts is an important issue for hospital functionality and disaster preparedness.

A considerable amount of literature has been published on hospital resilience and post-earthquake functional recovery. These studies have shown that hospital functionality depends on structural damage, non-structural damage, utility systems, organisational capacity, and recovery time [3–5]. Several studies have also focused on non-structural components in past earthquakes and reported that damage to these components may lead to loss of use and long repair periods [6,7]. However, hospital lifts are generally considered as a part of general building services, and detailed field observations on their post-earthquake damage are still limited. Lift systems contain many mechanical and structural components that may be affected by seismic motion. Counterweight frames, guide rails, rail brackets, guide shoes, suspension ropes, sheaves, landing doors, car frames, shaft walls, and seismic detection systems can influence the safe operation of lifts after earthquakes. Typical earthquake-related problems include counterweight derailment, guide rail or bracket deformation, rope displacement, landing door malfunction, car damage, and debris falling inside the shaft. These problems can be more critical in hospitals because patients and medical equipment may need to be transported immediately after an earthquake.

Earlier works on lift components, seismic effects, and emergency operation of lift installations provide a background for the present study. Guide rail brackets and fasteners were examined under earthquake loading, and different bracket designs were compared in terms of their structural response [8–10]. The behaviour of lift installations under emergency conditions and the damages observed in hospital lifts located in earthquake regions were also discussed in recent studies [11]. In addition, wire ropes and safety gear brake blocks were investigated using experimental, numerical, and image-processing-based methods [12,13]. Therefore, the present study extends these previous efforts by focusing specifically on field observations from hospital lifts after major earthquakes.

Turkey is located in a seismically active region, and many hospital buildings are located in earthquake-prone areas. The 2011 Van earthquake and the 2023 Kahramanmaraş earthquakes provided important field observations related to hospital lifts (Figure 1). These two earthquakes also occurred in different regulatory periods.

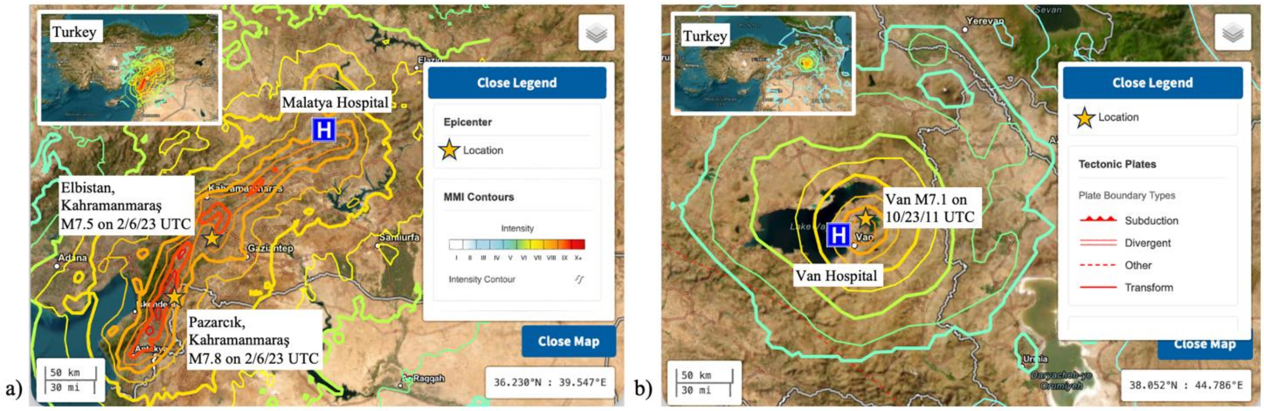

Figure 1 Location and epicentre map of the a) 2 June 2023 Kahramanmaraş Earthquakes [14] and b) 23 October 2011 Van earthquake [15] (adapted from U.S. Geological Survey)

The 2011 Van earthquake occurred before the implementation of EN 81-77 [16], provisions for lifts subject to seismic conditions in Turkey. The 2023 Kahramanmaraş earthquakes occurred after these provisions had become part of national lift regulations. Although these two cases do not provide a fully controlled comparison, they allow the evaluation of observed damage types under different regulatory conditions. This study presents field observations from hospital lifts inspected after the 2011 Van and 2023 Kahramanmaraş earthquakes. The observed damages are evaluated to identify common failure mechanisms and to discuss the remaining weak points of hospital lift systems. The seismic vulnerability of hospital lifts is first summarised. Then, field observations from the Van and Kahramanmaraş earthquakes are presented. Finally, the observed damage patterns are compared and practical design and operational implications are discussed.

2 HOSPITAL LIFTS AND FIELD OBSERVATIONS

Hospital lifts are exposed to different functional and mechanical demands compared with ordinary passenger lifts. They are used for patient beds, stretchers, wheelchairs, medical devices, staff circulation, visitors, service equipment, and daily hospital logistics. During and after an earthquake, these functions become more critical because the hospital must continue emergency response and patient transfer. Therefore, the seismic design of hospital lifts should consider both passenger safety and the continuity of vertical transportation.

According to EN 81-77, lifts subject to seismic conditions are classified by considering the design acceleration, which depends on seismicity, soil conditions, and the importance class of the building. Hospitals are included in the highest importance class because their integrity is vital for civil protection during earthquakes. The required precautions increase from Category 0 to Category 3. While Category 0 does not require additional seismic provisions, Category 1 includes measures such as prevention of snag points, counterweight retaining devices, rope retaining devices, compensation chain protection, guide rail systems, machinery, electrical installations in the shaft, and user information. Category 2 adds measures related to car and counterweight guide systems, car door locking devices, and special car behaviour in the case of power failure. Category 3 additionally requires a seismic detection system and seismic operation mode.

The most critical components for seismic safety are the counterweight system, guide rails, rail brackets, suspension ropes, sheaves, landing doors, car frame, and shaft equipment. Counterweight derailment, bracket deformation, rope displacement, and landing door malfunction may prevent safe operation after an earthquake. Therefore, mechanical retaining measures and active seismic detection systems should be considered together, especially for hospital lifts that are expected to support post-earthquake service continuity.

2.1 Field Observations after the 2011 Van Earthquake

The 2011 Van earthquake occurred on 23 October 2011 in eastern Turkey with a moment magnitude of Mw 7.1. Since the event occurred before the implementation of EN 81-77 provisions in Turkey, the inspected lifts were not designed according to the current seismic lift requirements. Therefore, the observations from this earthquake provide useful information about the behaviour of hospital lifts in the pre-standard period. Representative examples of these damage types are shown in Figure 2.

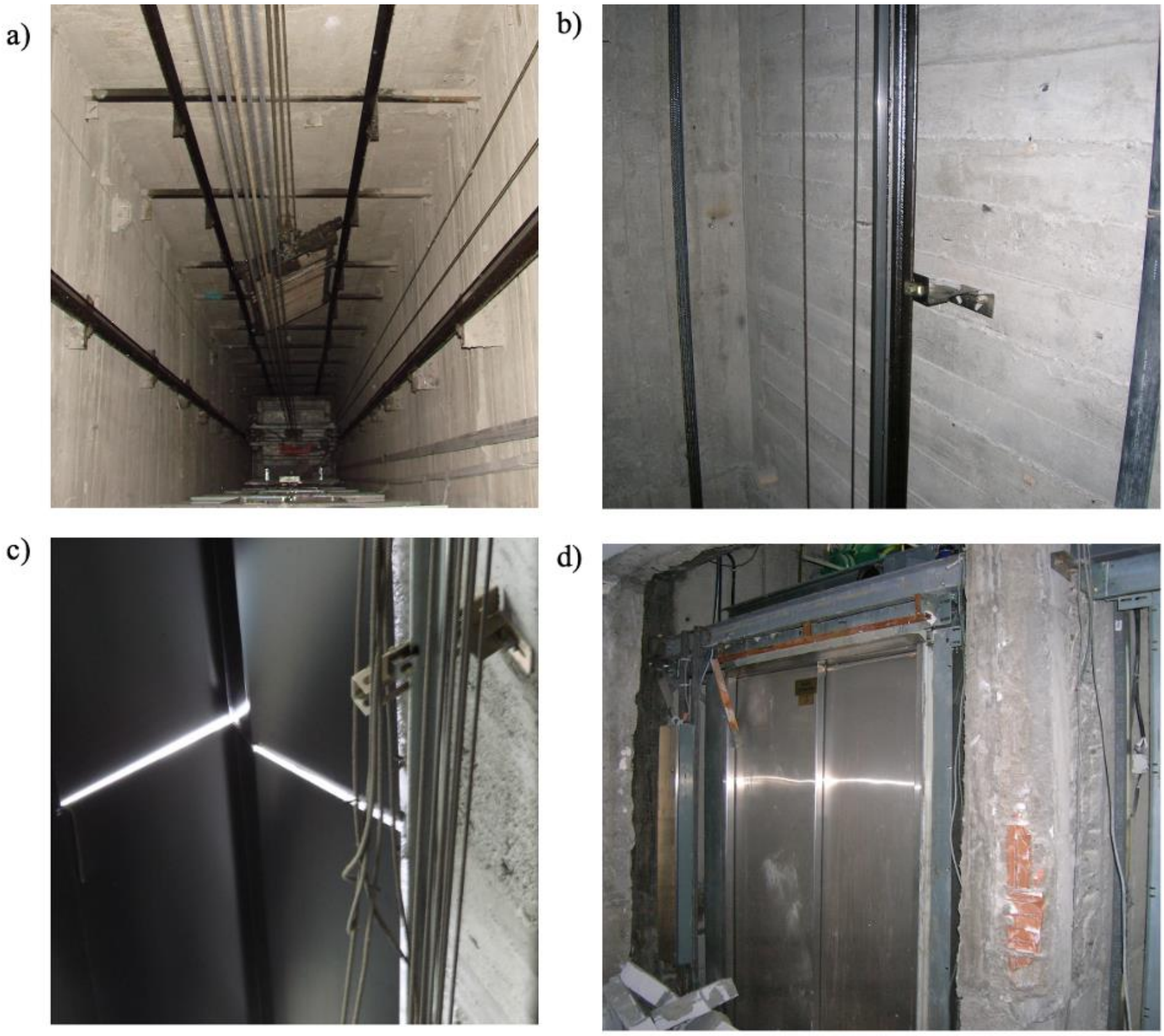

Figure 2 Damage observed in hospital lifts after the 2011 Van earthquake: (a) counterweight derailment, (b) guide rail/bracket damage, (c) rope displacement, and (d) landing door damage

After the earthquake, 25 lifts were inspected in two hospitals, including Van Speciality Hospital and Medical Park Hospital. The inspected lifts had different configurations, including hydraulic, machine-room, and machine-room-less systems. A common feature was the use of rigid guide shoes and concrete counterweights. At Van Speciality Hospital, the hydraulic lift did not show visible mechanical damage, while two machine-room lifts were not operational mainly due to landing door problems. More severe damage was observed at Medical Park Hospital. Counterweight derailment, guide rail/bracket damage, landing door damage, shaft wall debris falling onto the car roof, and suspension ropes leaving the sheaves were detected in several lifts. The 2011 Van observations show that lift failure may occur even when the main building structure remains usable. These findings are used as the pre-standard reference case in the comparative assessment of this study. In addition to the observed damage to the elevator components, structural damage was also observed in the hospital building, particularly in the elevator shaft walls, with debris falling onto the car roof.

2.2 Observations after the 2023 Kahramanmaraş Earthquake

On 6 February 2023, two major earthquakes occurred in the Pazarcık and Elbistan districts of Kahramanmaraş and affected a large region in southern and eastern Turkey. Many hospitals in the region had to continue their service under difficult post-earthquake conditions. Representative examples of the observed bracket damage and seismic sensor arrangement are shown in Figure 3.

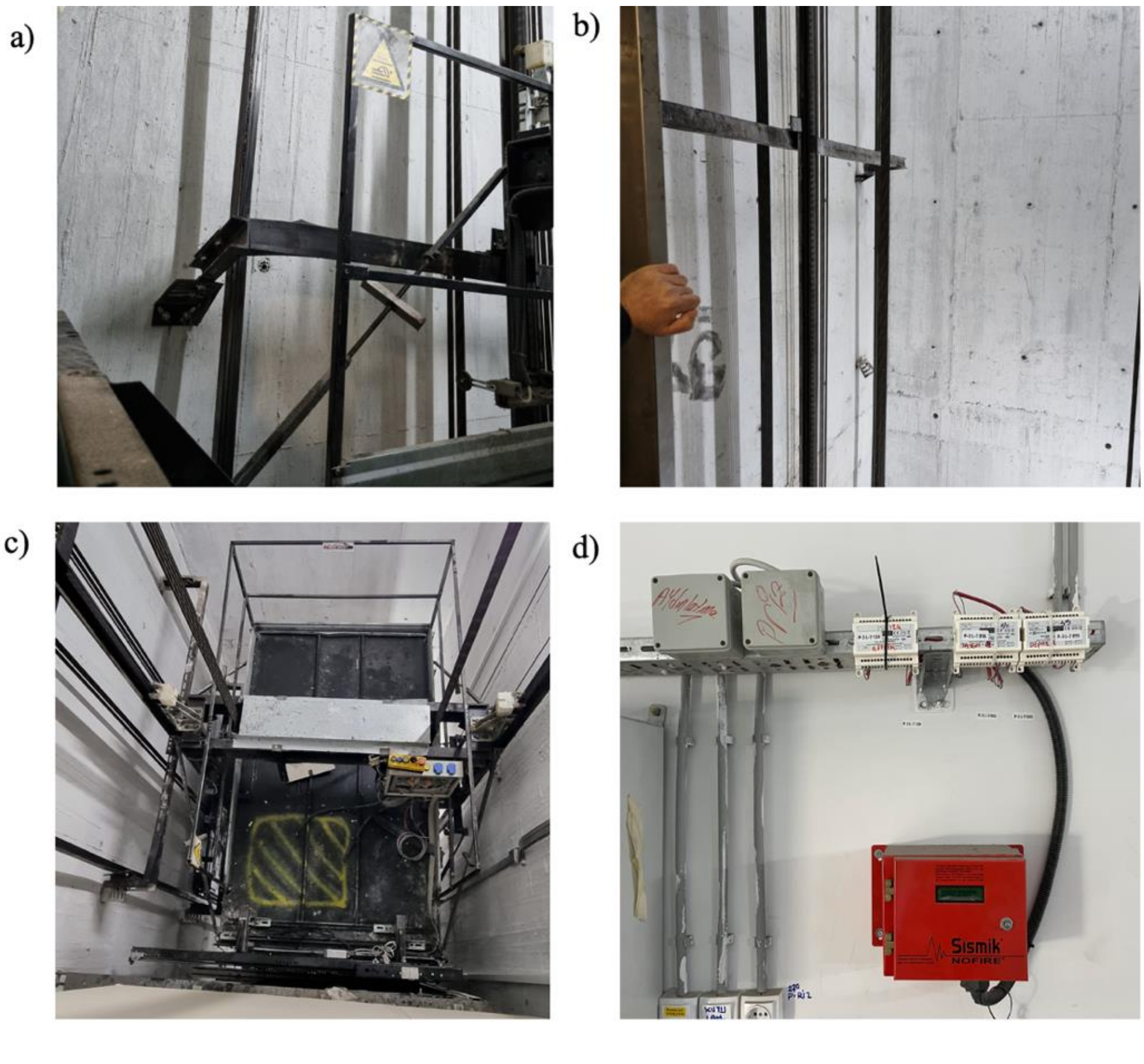

Figure 3 Damage and seismic safety observations in hospital lifts after the 2023 Kahramanmaraş earthquakes: (a) guide rail bracket deformation, (b) damaged bracket region, (c) car, and (d) seismic sensor installed in the lift system

The observations related to hospital lifts are mainly based on field examinations carried out in Malatya. In Malatya, 16 lifts were inspected after the earthquakes. The inspected lifts included machine-room, machine-room-less, and hydraulic systems. In machine-room and machine-room-less lifts, counterweight derailment, counterweight shoe damage, guide rail bracket damage, counterweight slab damage, and guide rail bending were observed. No visible damage was recorded in the inspected hydraulic lifts. These observations indicate that the counterweight assembly and guide rail support system remained the most critical components in the 2023 damage sample.

Additional observations were made at Malatya Turgut Özal University Training and Research Hospital, which included 51 lift units in different blocks. Among these units, eight machine-room lifts with a capacity of 2500 kg and two machine-room-less lifts with a capacity of 1600 kg were equipped with seismic sensors. These sensors were activated during the earthquakes. Some guide rail brackets in the machine-room lifts were deformed or damaged, while rope derailment from sheaves was not observed.

The 2023 observations show a different damage pattern compared with the 2011 Van earthquake. Rope displacement from sheaves and widespread landing door faults were not dominant failure modes, and seismic sensors were activated in several lifts. However, bracket deformation and counterweight-related damage show that some critical weak points continued in the post-standard period. The observed damage was limited to the elevator components within the hospital building. No signs of structural damage to the hoistways, machine rooms, or landing areas were observed.

3 COMPARATIVE ASSESSMENT

The field observations from the 2011 Van and 2023 Kahramanmaraş earthquakes show both similar and different damage patterns. These two cases should not be considered as a fully controlled comparison because the inspected hospitals, lift types, installation years, maintenance conditions, local ground motions, and building responses were different. However, the observations provide useful information about the weak points of hospital lifts under seismic effects. The 2011 Van earthquake represents a pre-standard case for EN 81-77 provisions in Turkey, while the 2023 Kahramanmaraş earthquakes represent a post-standard case. A comparative summary of the observed damage patterns is presented in Table 1.

Counterweight-related problems were the most repeated failure mode in both earthquake cases. In Van, counterweight frame derailment was observed in several inspected lifts. In the 2023 Malatya sample, counterweight derailment, shoe damage, and counterweight slab damage were also recorded. Guide rail and bracket damage was another common problem. These observations show that the counterweight system and guide rail support system should be considered together in seismic lift design. Some damage types were more dominant in the 2011 Van observations. Landing door faults, rope displacement from sheaves, and shaft wall debris falling onto the car roof caused operational problems in several lifts. In the 2023 Malatya sample, these damage types were not dominant, and rope derailment from sheaves was not observed in the inspected hospital lifts. The activation of seismic sensors in Malatya also indicates that active seismic safety systems can contribute to safer lift behaviour. However, the observed bracket damage and counterweight-related problems show that mechanical design measures and active detection systems should be considered together.

The comparison shows that some failure modes, such as rope displacement and widespread landing door faults, were less prominent in the 2023 observations. On the other hand, counterweight-related instabilities and guide rail support damage continued to be important weak points. Therefore, the results suggest a partial improvement in post-earthquake lift behaviour after the adoption of seismic provisions, but they also show that further attention is required for counterweight stability, guide rail brackets, anchorage details, and post-earthquake inspection procedures.

Table 1 Comparative summary of observed damage patterns after the 2011 Van and 2023 Kahramanmaraş earthquakes

Observed issue	2011 Van	2023 Malatya	Interpretation
Counterweight frame derailment	Frequently observed in several inspected lifts	Observed in MR and MRL lifts	Persistent weak point
Counterweight shoe or slab damage	Observed in damaged counterweight systems	Observed in inspected MR/MRL lifts	Requires better restraint of counterweight blocks
Guide rail / bracket deformation	Observed together with counterweight problems	Observed in some MR lifts	Bracket and anchorage design remains critical
Landing door faults or damage	Common and caused loss of operation in some lifts	Not dominant in the Malatya sample	Possible improvement, but sample-dependent
Rope derailment from sheaves	Observed in MRL lifts	Not observed in inspected sensor-equipped lifts	Rope retaining measures may reduce this risk
Shaft wall debris on car roof	Observed in MRL lifts	Not dominant in the Malatya sample	Shaft integrity and debris protection remain important
Hydraulic lift damage	No visible damage in inspected example	No visible damage in inspected hydraulic lifts	Should be interpreted cautiously due to limited sample
Seismic sensors	Not applicable in inspected pre-standard lifts	Present and activated in several lifts	Positive contribution to emergency operation

4 DESIGN AND OPERATIONAL IMPLICATIONS

The field observations show that hospital lift safety during earthquakes cannot be improved only by adding a seismic sensor. Mechanical components, shaft arrangement, control logic, and post-earthquake inspection procedures should be considered together. In particular, counterweight stability, guide rail support systems, rope retaining measures, and emergency operation functions remain the main issues for hospital lifts in seismic regions. The counterweight system should be one of the first components checked in seismic lift design. In both earthquake cases, counterweight-related problems were observed. Therefore, counterweight frames should be designed to prevent displacement of counterweight blocks during seismic motion. Concrete blocks should be mechanically restrained inside the frame, and the frame should be sufficiently rigid to prevent the blocks from jumping out or damaging the car and shaft components.

Examples of retaining devices for the car and counterweight systems are shown in Figure 4. These precautions are especially important for hospital lifts because even local damage in the counterweight system may cause long service interruption. Guide rail brackets, rail connections, and anchorage details should be designed considering the seismic design acceleration. The car, counterweight, guide rails, brackets, and fixing elements should be evaluated together. Ropes, sheaves, governor ropes, compensation chains, and travelling cables should also be protected against displacement and snagging. These measures can reduce the risk of rope derailment, shaft damage, and secondary failures after seismic motion.

Emergency operation and post-earthquake inspection procedures should also be defined specifically for hospital lifts. In seismic lift categories where special operation is required, the lift should be able to move the car to the next possible landing in case of normal power failure. For Category 3 lifts, seismic detection systems should activate the seismic operation mode, cancel registered calls, prevent new calls, and move the lift at reduced speed to a suitable landing when possible. Before returning the lift to normal service, the counterweight frame, guide rails, brackets, anchors, ropes, sheaves, landing doors, car frame, shaft walls, and seismic sensor system should be checked. Priority should be given to stretcher and patient-bed lifts because they are directly related to emergency healthcare operations.

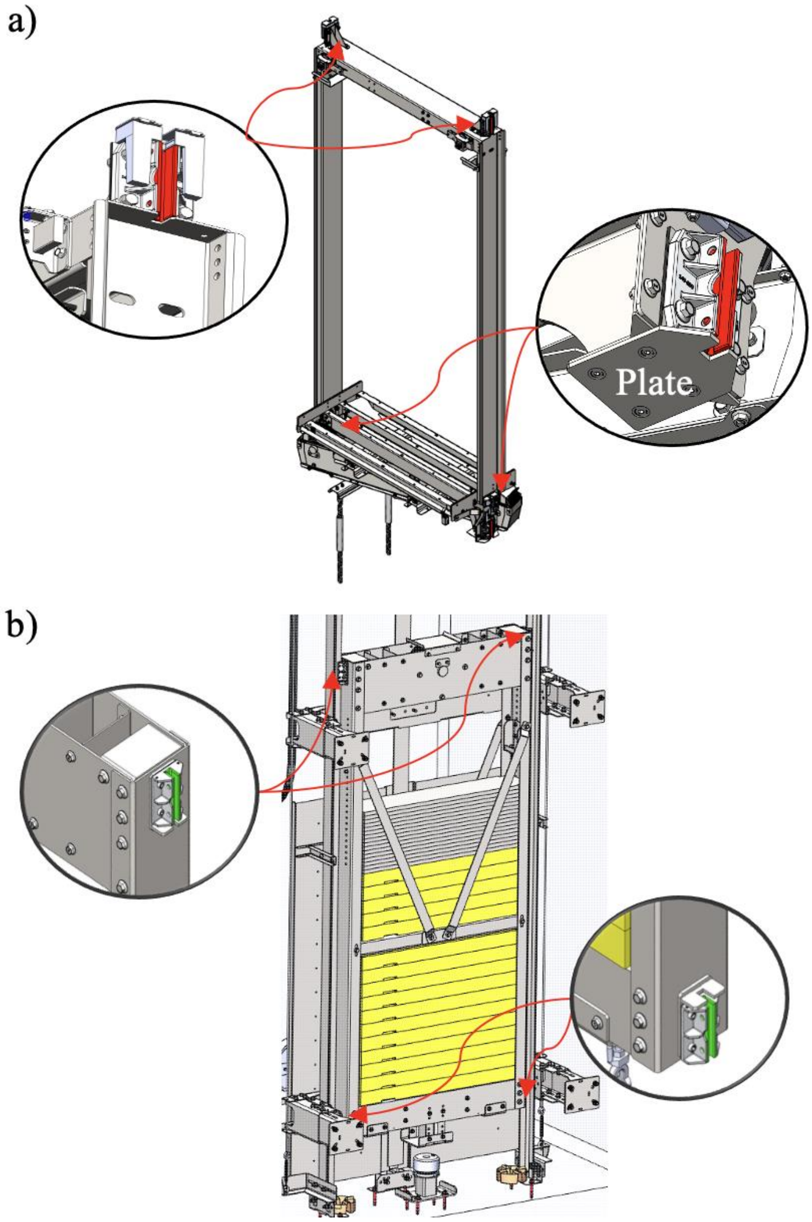

Figure 4 Examples of seismic retaining devices: (a) car retaining device and (b) counterweight retaining device

Overall, the design and operation of hospital lifts in seismic regions should be based on a combined approach. Passive mechanical precautions such as counterweight retaining, bracket strengthening, and rope protection should be used together with active systems such as seismic sensors and emergency return operation. This combined approach can reduce passenger entrapment, limit mechanical damage, and support the post-earthquake functionality of hospitals.

5 CONCLUSION

This study evaluated field observations from hospital lifts inspected after the 2011 Van and 2023 Kahramanmaraş earthquakes. The observations showed that hospital lifts are critical non-structural systems for post-earthquake functionality because their failure can affect patient transfer, emergency response, and internal hospital logistics. Counterweight-related problems and guide rail support damage were identified as the most persistent weak points in both earthquake cases. In the 2011 Van observations, counterweight derailment, landing door faults, rope displacement, shaft debris, and bracket deformation were observed, while in the 2023 Malatya observations, rope displacement and widespread landing door faults were not dominant and seismic sensors were activated in several lifts. These findings suggest a partial improvement in post-earthquake lift behaviour after the implementation of seismic provisions; however, the observations do not provide a fully controlled statistical comparison. Further attention is required for counterweight retaining systems, guide rail brackets, anchorage details, rope protection, seismic detection systems, and post-earthquake inspection procedures. For hospitals located in seismic regions, passive mechanical precautions and active emergency operation systems should be considered together to reduce passenger entrapment, limit mechanical damage, and support the continuity of hospital services after major earthquakes.

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Where and When: How Continuous Lift Monitoring Answers the Two Questions That Drive Service Efficiency

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Keywords: lift monitoring, IoT, adaptive baseline, anomaly detection, predictive maintenance, sensor fusion, fault detection

Abstract. Effective lift service has always depended on two questions: where is the problem, and when did it start? In the absence of continuous monitoring, answers to both questions arrive late, filtered through tenant callbacks, manual inspection logs, and technician recall. This paper examines how a controller-agnostic IoT platform, deployed across a heterogeneous fleet of commercial, transit, and healthcare lift installations, changes the answer to both questions in practice. Central to the approach is the absence of modelled baselines. Instead, two algorithms based on isolation forests and adaptive windowing are presented which detect anomalies by different methodologies to cover different kinds of anomalies. This approach is contrasted with fixed global threshold alerting, which the authors implemented and subsequently replaced following significant false positive rates. Operational case studies illustrate the practical outcomes. The paper discusses the known limitations of adaptive baseline methods, including the initialisation period required before reliable detection is possible, and the latency in alert resolution once a fault has been cleared.

1 INTRODUCTION

The lift service industry operates under a fundamental information problem. A fault develops gradually, often over days or weeks, but becomes visible to the service organisation only when a passenger reports it, typically by telephone, after the lift has already stopped or degraded to the point of inconvenience. By that point the fault has progressed further than necessary, the response is reactive rather than planned, and the dispatched technician may arrive to find the lift running again, having recovered on its own.

Estimates of fault-driven callout volumes illustrate the scale of this problem. Customer interviews concerning a 500-lift fleet operated by an independent service provider indicated approximately 1,000 callback visits annually. Approximately 47% of these were attributable to temporary shutdowns from which the lift had already recovered by the time a technician was dispatched, representing avoidable trips that could be eliminated with real-time status visibility. A further 12% were attributable to environmental causes addressable through physical monitoring of the shaft environment. The combined cost of avoidable dispatch alone was estimated at a minimum of USD 176,000 per year for a fleet of this size, based on an average callout duration of 1.5 hours at USD 250 per hour.

The technical precondition for addressing this problem is continuous, structured data from each lift unit. Various approaches have been explored in the literature. Accelerometer-based logging without controller access, as demonstrated by Peters and Peters [1], provides kinematics data including trip distance, velocity, and floor position. Sensor fusion approaches combining optical, accelerometric, and environmental sensors have been applied to door fault detection [2]. Machine learning methods trained on vibration signatures have demonstrated high classification accuracy for specific fault classes under laboratory conditions [3] [4]. Simulation-based approaches have been used to generate synthetic fault data for training condition monitoring models [5].

The laboratory approaches, while technically rigorous, share a common constraint: they require labelled examples of fault conditions in advance. In a real heterogeneous fleet, this constraint is significant. Fault events are rare relative to normal operation; labelled fault data is therefore scarce. More importantly, what constitutes normal behaviour varies substantially between units. A door closing time of 3.4 seconds may be unremarkable for one lift and indicative of developing friction in another. A gap in rides of 40 minutes may be expected overnight and anomalous at midday. Fixed global thresholds cannot accommodate this variability without either generating excessive false positives or missing genuine degradation.

This paper describes a different approach. Rather than training a model on labelled fault examples, the system constructs a per-unit baseline from each lift's own operational history and detects deviations from that baseline using an adaptive windowing method. No controller access is required. The method is applied across three signal domains: ride frequency (for shutdown detection), door behaviour (for door health and damage detection), and ride quality (for mechanical degradation detection). The approach is grounded in the adaptive windowing framework of Bifet and Gavaldà [6] and the barometric floor-level positioning methods described by Li et al. [7].

The paper is structured as follows. Section 2 describes the sensor architecture. Section 3 describes the isolation forest and the adaptive detection methods. Section 4 contrasts the adaptive approach with the fixed threshold approach previously in use. Section 5 presents two operational case studies. Section 6 discusses limitations and directions for further development. Section 7 concludes.

2 SYSTEM ARCHITECTURE

The monitoring platform described in this paper is hardware-agnostic. It operates alongside the lift controller without modification to the certified safety chain, consistent with the architectural principles described by Smans [8]. Data collection is performed by two primary sensing elements installed on the lift cabin: a light curtain and a gateway device. The light curtain is a safety sensor already present on most modern lifts for door obstruction detection. In the monitoring context, its beam interruption pattern provides a continuous record of door open and close events, passenger presence inference, and door cycle counts. The gateway device contains an accelerometer, a barometric pressure sensor, and a temperature and humidity sensor, and communicates via LTE or Ethernet to a cloud analytics platform.

Floor position is determined from barometric pressure using the method described by Li et al. [7], which exploits the measurable pressure differential between floors in enclosed building shafts. This approach provides floor-level resolution without requiring encoder access or controller integration. The accelerometer provides vertical acceleration data from which ride kinematics are derived: trip direction, peak speed, jerk, and vibration intensity per floor, following the analytical framework of Peters and Peters [1]. The light curtain provides door cycle timing, panel-level vibration, obstacle counts, and a direct measure of whether each door cycle completed its full range of travel.

Together, these three sensing elements – the light curtain, accelerometer, and barometer – produce a continuous structured data stream characterising each lift unit across three domains: what the cabin is doing (ride kinematics), what the doors are doing (door events), and where the cabin is (floor position). All data is timestamped at the gateway and transmitted to the cloud platform where baseline construction and anomaly detection are performed. No proprietary controller protocol is required at any stage.

3 ANOMALY DETECTION

In this section, we are presenting two approaches: isolation forests as an unspecified anomaly detection means, and adaptive windowing as a means of detecting specific anomalies.

3.1 Adaptive windowing for anomaly detection

Windowed anomaly detection is a tool for detecting ad hoc changes on single-dimensional time series, as they often appear when things break or spring out of adjustment. Windowed anomaly detection does not need any baselines.

This feature is derived from the ADWIN algorithm [6] and works by comparing the left and right sides of a window via the Mean Absolute Error (MAE) method. In case of an anomaly within the window, the MAE becomes quite large as the mean is no longer a good approximation of the data in the window. When slicing the window into a right and left side, the MAE for both windows becomes minimal when the slicing happens exactly at the location of the anomaly. This causes the window to split into two sides, with each being stable in its own regard.

Given a window W of size n with t_i being the timeseries data at index i as

$$W_n = \{t_i | \forall i \in \mathbb{N} \; with \; 0 \le i < n\}. \tag{1}$$

Splitting the window at position $k < n$ into a left and a right side reveals

$$\begin{aligned} W_{n,k} &= W_{left,n,k} \cup W_{right,n,k} \\ &= \{t_i | \forall i < k\} \cup \{t_i | \forall i \ge k\} \end{aligned} \tag{2}$$

and subsequently the MAE of window size n at splitting point k as

$$MAE_{n,k} = \left\{ \left| x_i - \underset{\forall i}{\operatorname{mean}}(x_i) \right| \mid \forall i, 0 \le i < k \right\} \cup \left\{ \left| x_j - \underset{\forall j}{\operatorname{mean}}(x_j) \right| \mid \forall j, k \le j < n \right\}. \tag{3}$$

Finally, the MAE of the entire window comes to

$$MAE_n = \{\operatorname{mean}(MAE_{n,k}) | \forall k, 0 \le k < n\} \tag{4}$$

The range between the minimum and maximum MAE within a window is a good measure for whether an anomaly is present within the window. Depending on the type of data that is analysed, both static and dynamic (data-driven) thresholds show good results. The position k with the minimal MAE is the temporal position of the anomaly.

This method just looks at data cohesion within a given window. A baseline of any sort is not required.

The key property of the modified ADWIN algorithm relevant to this application is its mathematical guarantee on false positive and false negative rates. The algorithm detects change when two sufficiently large sub-windows of the current window exhibit means that are statistically distinct beyond a configurable bound. This provides a principled basis for the alert threshold that is specific to each unit's own variance, rather than a global engineering judgement.

3.2 Isolation forest

An isolation forest [9] is a model-based classification method that can isolate anomalies in a multi-dimensional dataset. It has the advantage that one does not need to model normal behaviour upfront, which is not known on a per-lift basis. The isolation forest is used to answer the question: is the most recently observed behaviour different to the behaviour observed throughout the last weeks?

Once this question gets answered positively for a point in time, a detailed statistical analysis on a per-lift basis is carried out to determine the relevance of the anomaly and determine the offending lift component. This was modelled by expert knowledge to look for certain behavioural anomalies to identify the most likely faulty component and the location of the fault.

Both the isolation forest and the statistical analysis have problems which make them hard to use in isolation. The statistical analysis is hard to parameterise between false positives and false negatives. In contrast, the isolation forest lacks explainability. With SHAP, the isolation forest can reveal the most dominant dimensions in the anomaly. However, this still does not reveal the concrete problem in terms of lift domain knowledge.

The combination of both methods has shown good results for detecting door failures. In a fleet of 178 lifts observed over four months, 1.7 million tumbling windows of 15 minutes each have been analysed. In that dataset, the isolation forest reported 1.24% of them as outliers. The statistical analysis was loosely trimmed and reported 1.7% of the bins as anomalies. The intersection of these two sets left only 264 windows which were flagged by both algorithms. These windows were then combined into consecutive events and alerted to customers as door behaviour anomalies. The backing of the expert-modelled statistical analysis made the alerts understandable to the lift mechanics.

4 CONTRAST WITH FIXED THRESHOLD ALERTING

Fixed thresholds are inherently limited because they cannot adequately capture either differences between lifts or changes in the behaviour of the same lift over time. For this reason, an adaptive thresholding approach was adopted.

An earlier implementation relied on global static thresholds, whereby alerts were triggered when a metric exceeded a predefined limit (for example, excessive door cycling between rides or vibration above a fixed amplitude). In practice, this approach produced a high false-positive rate, with the system generating up to 30 alerts per day for fewer than a hundred lifts. Most alerts reflected normal operational variability rather than emerging faults, reducing user confidence and limiting practical value.

Following implementation of adaptive baseline detection, alert frequency fell to approximately one alert per month and lift. This reduction reflected improved specificity rather than reduced sensitivity. As shown in section 5, genuine fault conditions were detected earlier and with greater precision under the adaptive approach.

5 FIELD OBSERVATIONS

Two field observations are presented, each illustrating a different signal domain and maintenance outcome. Lift manufacturers are not revealed, and customer information has been anonymised.

5.1 Door component degradation: roller off-track detection

The first case concerns a commercial lift installation monitored over a five-month period from August to December 2025. The door health analysis for this unit is shown in Figure 1, which presents two metrics tracked at daily resolution. The dashed blue vertical line marks the date on which a door health alert was detected by the system (7 September 2025). The dashed red vertical line marks the date which the alert lists as the behaviour change date (3 September 2025). The four days in between were used by the system to gain confidence on whether this is a permanent change.

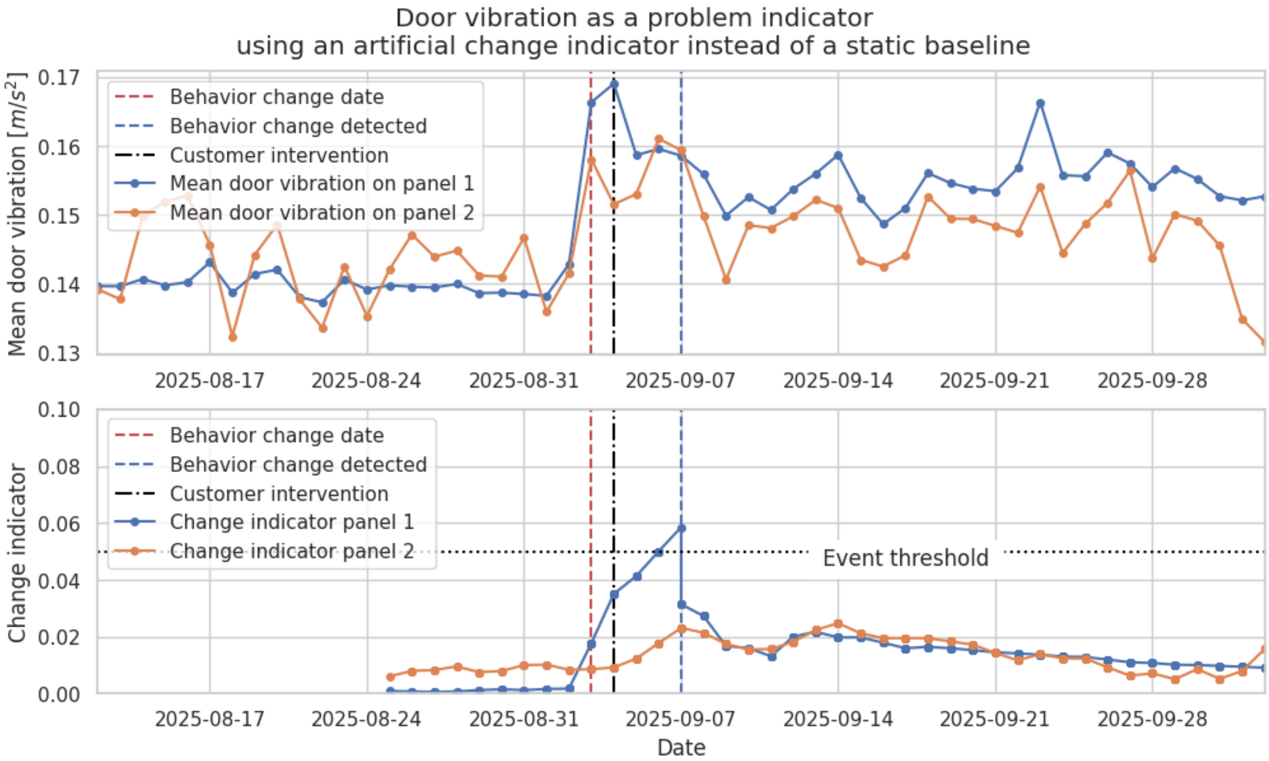

Figure 1 Multi-signal door health analysis for a commercial installation.

The dashed red line marks the detected behaviour change date. The dash-dotted black line marks the unrelated replacement of the roller. The blue dashed line marks the point in time when the anomaly was detected. The bottom plot shows the increase of the change indicator, easily understood as the system building confidence. Following roller replacement (black dashed line), the vibration signal stabilises at a new operating level while the adaptive change indicator returns below the detection threshold after sufficient post-repair data have been accumulated.

Based on our alert, a technician inspected the lift on 4 September 2025 and found that one of the door rollers had moved off track following an unreported impact on the door panel. The roller was replaced, preventing further wear progression and avoiding a potential door jam that would require emergency attendance.

The upper graph in Figure 1 shows that the mean door vibration changes significantly after the maintenance intervention. In particular, both door panels exhibit a new stable vibration level with increased fluctuations compared to the pre-fault state. Although the repaired door no longer behaves identically to the pre-fault condition, it settles into a consistent operating regime characteristic of the new roller. This change in normal operating behaviour demonstrates why fixed baselines would require manual recalibration after maintenance.

The lower graph illustrates how the adaptive windowing algorithm responds to this change. The change indicator rises as evidence for the behavioural shift accumulates, triggering the anomaly alert. Following the roller replacement, the indicator gradually decreases below the event threshold as sufficient post-repair observations become available and the algorithm establishes the repaired behaviour as the new normal.

This case illustrates the core advantage of trend detection over threshold detection. The key was an early shift in the statistical distribution of vibration measurements, not a violation of an absolute limit. The adaptive windowing captured the shift; a fixed threshold for all lifts would not have.

5.2 Door damage detection: Multiple anomalies detected with one algorithm

With the combination of isolation forest and statistical post-processing, multiple different kinds of anomalies can be detected. Figure 2 illustrates how the two-stage detection process identifies operational anomalies over several consecutive days.

Each data point in the upper graph represents the anomaly score computed for a 15-minute tumbling window. Windows identified as anomalous by the isolation forest (brown dots) are subsequently evaluated using the expert-defined statistical analysis described in Section 3.2. The shown graphs of ride and door movement counts, and the number of obstacles in the light curtain, are the main input factors for the statistical post-processing. Only windows classified as anomalous by both methods are retained. Consecutive anomalous windows are merged into a single event, which is displayed as a green shaded region. The width of each green region therefore represents the duration of the detected abnormal behaviour rather than a single timestamp.

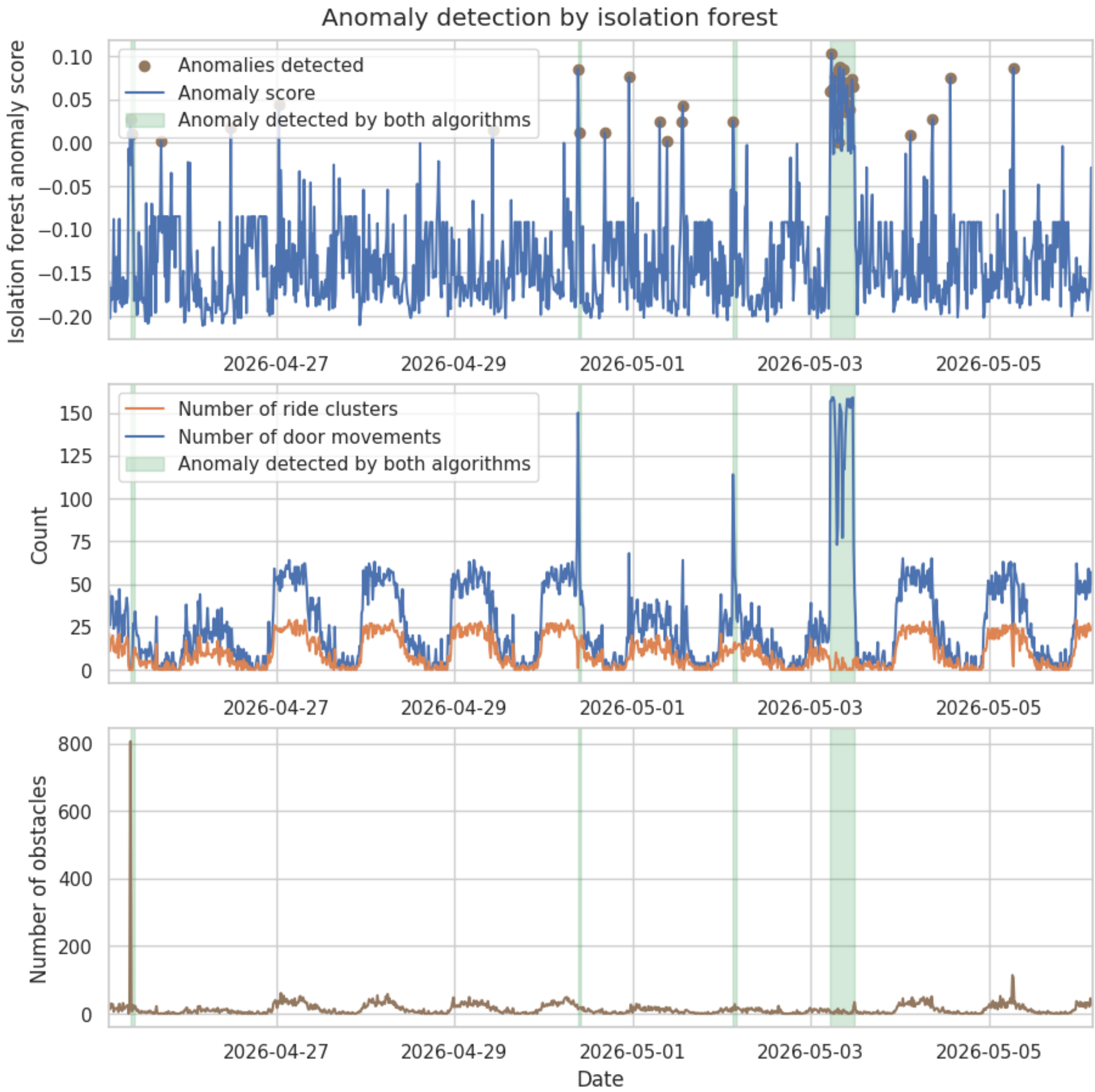

Figure 2 Results of the described anomaly detector

The top graph shows the isolation forest anomaly score, with brown markers indicating windows classified as anomalous by the isolation forest alone. The middle graph shows the number of door movement clusters (blue) and ride clusters detected by the light curtain (orange). The bottom graph shows the number of obstacle detections recorded by the light curtain. Green shaded regions indicate anomaly events triggered by the isolation forest and confirmed by the statistical post-processing algorithm.

The first detected anomaly was a blocked door. The number of obstacles in the light curtain jumps up, followed by no further door or car movements. The simultaneous increase in obstacle counts and absence of subsequent activity indicates that the door failed to complete normal operation, resulting in a sustained interruption of service.

The latter three anomalies are different kinds of repeated door cycling without rides (second anomaly, 30 April) and with lift rides (anomalies on 2 and 3 May). In these cases, repeated door movements occur without the expected correspondence between passenger activity, obstacle detections and car movement, producing an abnormal multi-sensor pattern that is recognised by both the isolation forest and the statistical post-processing.

Also, the slightly unusual behaviour on 24 April was not flagged, as this constitutes only an above-average usage period where all monitored signals remain mutually consistent. Although passenger traffic increased, the relationships between door movements, passenger clusters and obstacle counts remained consistent with normal operation. Consequently, the statistical analysis rejected the isolation forest output, preventing a false positive.

6 DISCUSSION

6.1 Relationship to laboratory-based approaches

The isolation forest approach described in this paper addresses a different problem from the supervised machine learning methods applied in laboratory settings by Kaczmarczyk et al. [3] [4] and Lin and Roivainen [5]. Laboratory approaches achieve high accuracy in fault classification because they control the conditions: a known fault is introduced into a test rig, labelled data is collected, and a classifier is trained to distinguish fault classes from normal operation. The resulting models can identify specific fault types, such as inner bearing ring damage or door lock mechanism failure, with high precision.

The operational constraint is that labelled fault data at scale is difficult to obtain in real fleet deployments. Faults are rare relative to normal operation. The specific failure modes that occur in the field may not match those represented in the laboratory dataset. And the variability of real-world installations, in terms of manufacturer, age, configuration, and operating environment, limits the transferability of models trained on a specific test rig.

The isolation forest approach, on the other hand, is an unsupervised methodology and detects that something has changed from normal for a specific lift, localises the change to a component and floor, and timestamps it. This is complementary to, rather than in competition with, fault classification approaches. In a mature monitoring architecture, baseline-based anomaly detection could serve as a first-stage filter that flags candidate events for subsequent classification, with the classification stage applied only to the small subset of events that cross the detection threshold.

6.2 Known limitations

Three limitations of the current approach warrant explicit discussion.

The initialisation period means that the system cannot provide anomaly detection immediately upon installation. The length of the training period depends on the regularity of the unit's operating pattern. Service organisations should be informed of this constraint at the point of onboarding.

Alert resolution latency is a second limitation. The adaptive window shrinks when a change is detected, but grows again only as new stationary data accumulates. When a fault is repaired and the monitored signal returns to its baseline level, the system may continue to carry an active alert for some time while the post-repair window accumulates sufficient observations to confirm stability. This can be mitigated by manual alert clearance at the time of the technician visit, which requires integration between the monitoring platform and the service organisation's workflow.

The third limitation is that anomaly detection identifies change but does not identify the specific cause. The alert directs a technician to the right location and the right signal domain, but root cause determination remains a human task. This is appropriate for a safety-critical industry where maintenance decisions carry liability implications, but it means the system functions as an aid to technician judgement rather than a replacement for it.

6.3 Directions for further development

Several directions for further development are under active consideration. Further work on distinguishing vibration sources for specific components can lead to better characterisation of the malfunction. Maintenance event detection, the ability to identify from sensor data that a maintenance visit has occurred, would allow the system to automatically reset baselines following maintenance and reduce alert resolution latency. Multi-unit comparison, using aggregated fleet data to identify units whose baseline behaviour is systematically different from similar units in similar buildings, could surface latent issues that per-unit detection would miss. Integration with field service management systems would close the loop between alert generation and technician dispatch, enabling automated work order creation and structured feedback on alert accuracy.

7 CONCLUSION

This paper has described a controller-agnostic IoT monitoring architecture for lift installations that constructs per-unit adaptive baselines across three signal domains and detects anomalies as deviations from those baselines using an adaptive windowing method. The approach was motivated by the operational failure of fixed global threshold alerting, which generated up to 30 false positive alerts per day before being replaced, and was subsequently reduced to approximately one alert per month following the transition to adaptive baselines.

Three operational case studies demonstrate practical outcomes: early detection of door roller degradation through vibration trend analysis two weeks before absolute thresholds would have been crossed; characterisation of a door damage and incipient shutdown event through the fusion of independent barometric and light curtain signals; and detection of three shutdown events on a high-traffic unit, with the second shutdown independently corroborated by zero accelerometer activity across two separate light curtain sensors. A fourth operational outcome, run-on-arrival avoidance, is described as the most consistently quantifiable form of value for independent service providers, with an estimated minimum saving of USD 176,000 per year on a fleet of 500 units.

Three limitations are discussed: the initialisation period before reliable detection is possible, alert resolution latency following fault clearance, and the absence of root cause identification. Each is a known and characterizable property of the adaptive windowing approach rather than a fundamental constraint of the sensor architecture.

The isolation forest approach does not replace laboratory-based fault classification methods. It addresses the complementary problem of detecting that a change has occurred in a real heterogeneous fleet, without requiring labelled fault data or controller access. In doing so, it answers, more reliably and more specifically than fixed threshold alerting, the two questions that drive lift service efficiency: where is the problem, and when did it start.

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9 BIOGRAPHICAL DETAILS

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The Science Behind Lift Codes & Standards

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Keywords: Codes, Standards

Abstract. Codes and Standards at first glance appear to be an arbitrary collection of rules, regulations, and dimensions. However, most codes and standards are based on basic safety principles, known risks, and science.

The safety fundamentals behind codes and standards in ISO/TR 1107-1 for traction lifts are presented.

The risks to be addressed, as well as the persons and objects to be safeguarded, as defined in EN 81-1, are reviewed. Although EN 81-1 has been superseded by EN 81-20 and EN 81-50, the abbreviated list of risks in EN 81-1 is still valid and easier to understand.

The science, mostly physics, and how it is applied are explained in simple terms.

How the risks, safety fundamentals, physics, and standards are applied to safety gears, brakes, and buffers are explored.

1 INTRODUCTION

During my first week in the lift industry, I was introduced to both the State of California Elevator Safety Orders and the City of Los Angeles Elevator Code.

California had no minimum pit depth. For flexibility, I was instructed to ask for a 3'- 11" (1,194 mm) deep pit. However, the City of Los Angeles required a minimum pit depth of 4'– 0" (1,219 mm). I asked why Los Angeles wanted an extra 1" (25.4 mm) and was told that both codes require a pit ladder if the pit is 4' or deeper, and Los Angeles wanted a pit ladder for their older inspectors.

For the next thirty-three years, I assumed codes were just a set of arbitrary rules that had to be followed to successfully get through an inspection. Then I took a course at the University of Northampton titled *Codes and Standards* and learned that there was science behind most of the standards [1].

2 RISKS TO BE SAFEGUARDED

EN 81-1 identifies the following risks that need to be addressed and mitigated [2]:

a) shearing
b) crushing
c) falling
d) impact
e) trapping
f) fire
g) electric shock
h) failure of material due to:
    1) mechanical damage
    2) wear
    3) corrosion

Additionally, EN 81-1 requires loads in the car and the following persons to be safeguarded:

a) users
b) maintenance and inspection personnel
c) persons outside the lift well, the machine room and pulley room (if any)

3 ASSUMPTIONS

ISO TR 11071:2004 Comparison of worldwide lift safety standards Part 1: Electric lifts (elevators) states that the world's safety standards for lifts are based on a common set of assumptions about the following [3]:

1. Safe operation assured to 125% of rated load
2. Failure of electrical safety devices
3. Failure of mechanical devices
4. Imprudent acts by users
5. Neutralisation of safety devices during service
6. Car speed linked to frequency of mains (the frequency of the three-phase electrical supply)
7. Horizontal forces exerted by a person
8. Retardation

Each of these assumptions will be reviewed.

3.1 Safe operation assured to 125 % of rated load

It seems very logical to assume that passenger lifts can be overloaded. The amount to which they can be overloaded with people is limited by platform area.

For example:

1. The maximum platform area permitted by EN 81-20 for a 630 kg passenger lift is 1.66 m² [4].
2. A 630 kg lift is rated for 8 passengers.
3. It is assumed that a typical passenger will have a mass of 75 kg and occupy 0.21 m² of cabin floor area.
4. Eight passengers would then require a platform area of 1.68 m² (8 * 0.21).
5. A 630 kg lift must be able to safely transport a 25% overload or 786 kg.
6. The additional 158 kg represents 2 additional passengers (2 * 75).

In the example above, the lift can be seen to be fully occupied with 8 passengers. Therefore, it would be difficult for 10 passengers to enter this lift.

3.2 Failure of electrical safety devices

Electrical safety devices are typically homologated by a Notified Body or an equivalent organisation. Therefore, it is assumed that if properly manufactured, installed, maintained, and most importantly, inspected, they will function properly when needed.

3.3 Failure of mechanical devices

Except in accidents involving suspension means or partial brake failure, mechanical components are assumed not to deteriorate to a hazardous condition before the need for replacement is detected. This applies when they are built and maintained in accordance with good practice and safety standards.

3.4 Imprudent acts by users

It must be assumed that users of lifts will misuse lifts and therefore, lift engineers should consider this in their designs.

3.5 Neutralisation of safety devices during servicing.

It is understood that service technicians must at times use jumpers to bypass door locks, etc. Jumpers can inadvertently be left in place when a lift is returned to service. To prevent this condition, BS EN 81-1: 1998 +A3:2009 requires a Landing and Car Door Bypass Device. The device is easier to use than a jumper, and the car will not run on automatic with the device enabled.

3.6 Car speed linked to frequency of mains

Prior to the 1980s, many slow speed lifts used single or two speed AC motors. These motors were known as asynchronous motors or as squirrel cage motors, and operated at a speed that approximated a multiple of the supply frequency. The following equation can be used to define the motor speed in revolutions per minute (rpm) [5]:

$$N_s = \frac{60 \times f}{p \div 2} \quad (1)$$

Where: N_s represents synchronous speed in rpm

f represents frequency of the AC supply mains

p represents the number of poles of the motor

See Figure 1.

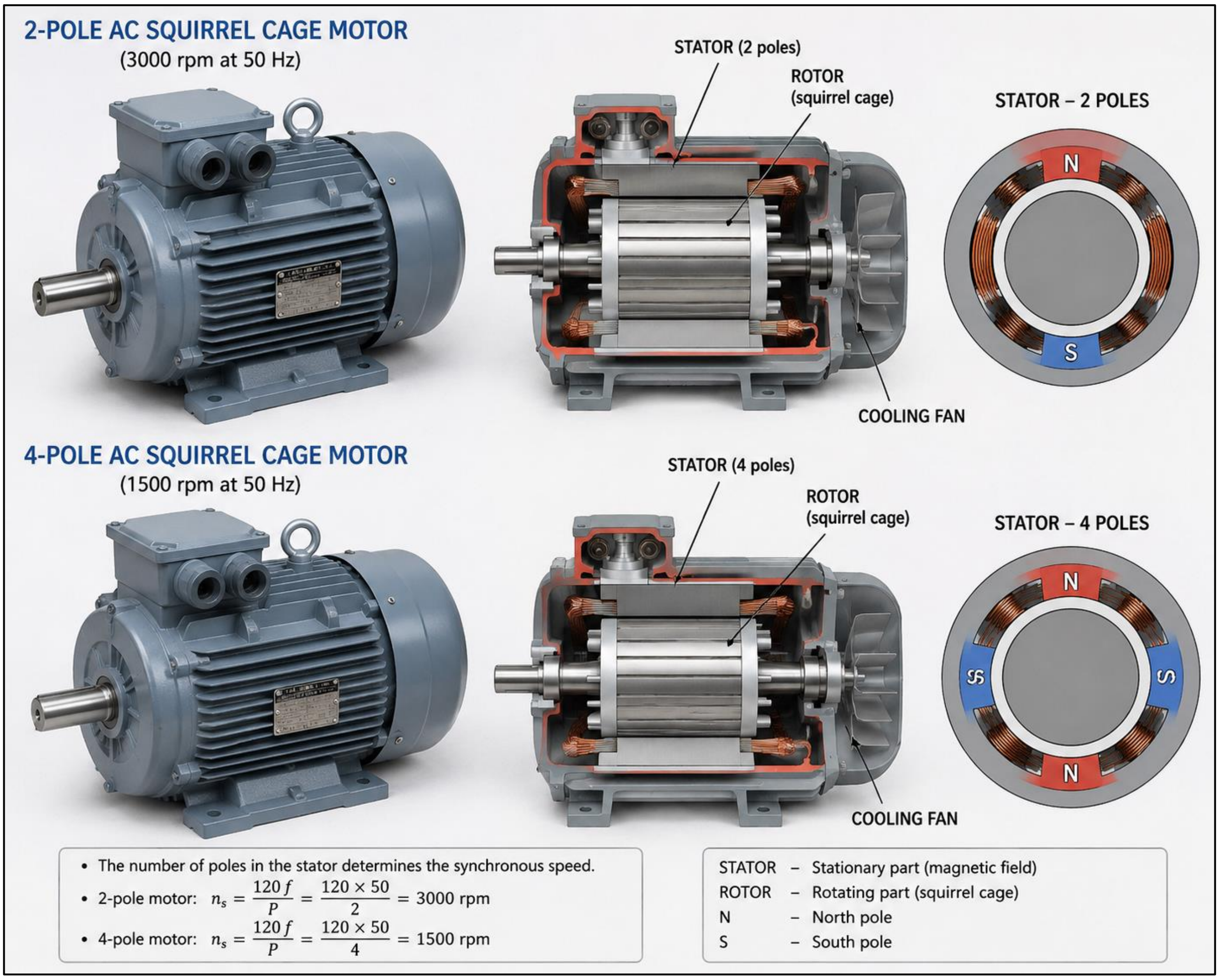

Figure 1 [6]

The actual speed of an asynchronous motor depends on the load [7]. If a fully loaded lift is going up, the motor rpm will be approximately 5% less than the synchronous speed. The same fully loaded lift travelling down will travel approximately 5% faster than synchronous speed.

If an AC machine is designed to operate at 1 m/s fully loaded in the up direction with 5% slip, then it will run in the down direction fully loaded at 1.1 m/s or 110% of rated speed.

The minimum tripping speed for governors is 115 % of the rated speed of a lift [4]. This speed prevents governors from tripping when the overspeed is due to the characteristics of a squirrel cage motor, whilst correctly sensing a true overspeed or loss of suspension.

3.7 Horizontal forces exerted by a person

One person can exert either of the following horizontal forces at a surface perpendicular to the plane at which the person stands [3]:

a) static force: 300 N.

b) force resulting from impact: 1,000 N.

When one imagines a 75 kg person either leaning against a cabin wall or hoistway door, the 300 N force seems reasonable, as does an impact force of 1,000 N.

Static forces of short duration may be exerted by the simultaneous deliberate acts of several people located immediately adjacent to each other at an interval of every 300 mm along the width of surfaces such as doors and cabin walls.

For this reason, codes and standards have rigorous static and dynamic tests of entrance doors, cabin doors, and cabin walls [3, 8].

3.8 Retardation

People have been found to be capable of withstanding an average vertical retardation of 1g (9.81 m/s²), such as during an emergency stop of a lift. Additionally, higher transient retardations have also been tolerated successfully.

ISO TR 11071 states that historically, this 1g value is not been shown to be unsafe for a vast majority of people [3].

This retardation assumption applies to every device that retards the velocity of a lift in all the world's codes.

4 STANDARDS APPLICATIONS

The following are examples of how Codes and Standards address risks and persons to be safeguarded based on the assumptions previously detailed.

4.1 Safety Gear, Progressive

Risk: Impact, Falling

Persons to be safeguarded: Users

Assumptions: Retardation, Car speed linked to frequency of mains

Discussion: Progressive safety gears are required to bring a fully loaded car to a stop with an average retardation rate of between 0.2 g_n and 1 g_n. The minimum safety application velocity is $1.15v_n$.

The reason EN 81 specifies a retardation rate of between 0.2 g_n and 1 g_n is to accommodate an empty car and a fully loaded car. If a fully loaded car decelerates at $1g_n$, then an empty car would decelerate at a significantly higher rate.

Example: Calculate the force required to decelerate a fully loaded lift with a capacity of 1,000 kg (Q) and an empty car weight of 1,700 kg (P) at a rate of 1 g_n. Newton's Second Law of Motion states the following [9]:

$$F = ma \tag{2}$$

Where: F represents force in Newtons

m represents mass in kilograms

a represents acceleration in meters per second squared

g_n represents the gravitational acceleration or 9.81 m/s².

In the case of a free-falling lift:

$$a = (g_n + k) \tag{3}$$

Where k represents the deceleration rate of the free-falling lift.

The retarding force in this case will equal 2,700 x 19.62, or 52,972 Newtons.

If the mass in the car is changed to 0 kg, then the total mass equals 1,700 kg, and if the retarding force of the safety gear remains 52,972 N, then the deceleration rate equals 2.18 $g_{n.}$

Solving for the maximum retarding force that can decelerate the empty car at $1g_n$ yields a value of 33,354N.

A retarding force of 33,354N would decelerate the fully loaded car at 2.54 g_n.

The example shown here has been simplified for clarity. A real example would include rope and compensation masses, kinetic and potential energy dissipation, and other variables.

The EN 81 code gives a reasonable range of deceleration rates so both the fully loaded and empty car can operate safely considering a more complete and complex set of variables.

4.2 Energy Dissipation Buffers

Risk: Impact

Persons to be safeguarded: Users

Assumptions: Retardation, Car speed linked to frequency of mains

Discussion: Energy dissipation buffers are required to bring a fully loaded lift car or counterweight travelling $1.15v_n$ to a stop at a deceleration rate of no more than $1g_n$. The retardation requirement is based on the retardation assumption, whilst the velocity requirement is based on the car speed being linked to the frequency of mains assumption.

4.3 Overspeed Governor

Risk: Impact, falling

Persons to be safeguarded: Users

Assumptions: Retardation, Car speed linked to frequency of mains

Discussion: Overspeed governors have a minimum tripping speed of $1.15v_n$. This is based on the car speed being linked to the frequency mains. A fully loaded car travelling down can exceed v_n . The minimum tripping speed requirement is to avoid setting the safety gear whilst the suspension means are intact.

Overspeed governors have a maximum tripping speed of approximately 1.25 v_n. This speed limit reduces the quantity of energy that must be dissipated by the safety gear and reduces the forces to which the lift equipment will be subjected.

The overspeed governor must be fitted with an electrical switch that will disconnect the hoist machine from the electrical mains and cause the mechanical brake to be applied. Whilst not a requirement of EN 81, this switch is commonly set at 1.15 g_n.

4.4 Mechanical Brake

Risk: Impact, falling

Persons to be safeguarded: Users

Assumptions: Retardation, Safe operation assured to 125 % of rated load, Failure of material (partial brake failure)

Discussion: Brakes are required to stop and hold 125% of rated load with a maximum deceleration rate of $1g_n$.

Two braking devices are required because it is envisioned that a partial brake failure can occur. A single mechanical brake must decelerate the car.

5 DISCUSSION

The components reviewed in the previous section safeguard passengers from a series of events, including loss of suspension, overspeed conditions, and failure to stop at terminal landings as follows:

a) Loss of suspension: The governor detects a loss of suspension and activates the safety gear at 1.25 v_n. The safety gear brings the car to a stop at a deceleration rate no more than 1 g_n.
b) Overspeed in the down direction, suspension intact: The governor detects the car speed is above 115% of v_n, and disconnects power to the motor and brake. The brake brings the car to a stop at a deceleration rate no more than 1 g_n.
c) Overspeed in the down direction with partial brake failure: The buffer brings the car to a stop at a deceleration rate no more than $1g_n$.
d) The car fails to stop at the lowest landing at a speed below 115% v_n: The buffer brings the car to a stop at a deceleration rate no more than $1g_n$.

These components safeguard the passengers or goods inside the cabin from zero to 100% of capacity.

6 CONCLUSIONS

This paper has shown that codes and standards for lifts are not just a set of arbitrary rules that must be followed to successfully get through an inspection, but rather a set of standards that are based on risks to be mitigated and a group of time-tested assumptions.

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BIOGRAPHICAL DETAILS

Rory Smith is a Consultant at Peters Research Ltd. He has over 57 years of lift industry experience, during which he held positions in research and development, manufacturing, installation, service, modernization, and sales. His areas of special interest are Machine Learning, Operations Management, Traffic Analysis, dispatching algorithms, and ride quality. Numerous patents have been awarded for his work.